Optimum parameters of Organic Rankine Cycle (ORC) power plant using coconut shell as fuel

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Abstract. The scarcity of energy sources is an important issue now. The increasing number of populations causes higher energy needs. The use of renewable energy as an alternative is a good solution. Organic Rankine Cycle (ORC) is a Rankine cycle that can work at low temperatures and pressures. The working fluid of ORC is an organic one such as R-134a refrigerant; because its boiling point is lower than that of water and has low environmental impact. In this study, work simulations were performed by using Cycle Tempo software to analyze the performance of the ORC system using coconut shells and to obtain optimum parameter variations based on thermal efficiency values. The simulated data consists of 12 variations of fuel rate parameters and mass flow rate. Based on the simulation results, 2.5 kg 2 GPM variation is obtained as the optimum parameter variation with a thermal efficiency value of 6.17%.

1. Introduction
The scarcity of fossil energy sources has become a major issue in the world when fossil energy sources have a limited amount and require a very long time to be formed again. Renewable energy is the energy that comes from sustainable natural processes so that it can replace fossil energy sources in the future. Renewable energy such as geothermal, wind energy, and solar energy are some examples of renewable energy [1]. Some of the research that has been done is the generation of Organic Rankine Cycle (ORC) systems, the working principle of ORC with Rankine cycle system is almost the same, the difference is only in the working fluid used ORC has a lower temperature and pressure compared to water in cycle Rankine. From an economic standpoint, it has a low maintenance cost, no additional fuel use, and low environmental impact [2]. According to Drescher and Brüggemann [3] electric power is usually generated in a process based on the Rankine cycle with water as a working fluid. The ORC process uses organic working fluid in contrast to water, the turbine expansion in the ORC system produces mostly not in the wet vapor phase but the gas phase higher than the condenser temperature.

Various types of ORC development using renewable energy sources have been done by Chinese et al. [4] that developed an ORC for biomass fuel for industrial districts. According to Tchanche et al. [5] in a study revealed that solar energy, biomass, and geothermal energy are considered as clean and environmentally friendly renewable energy sources suitable for ORC energy sources. Apart from the energy source, the most important thing in ORC is the type of working fluid used, not all types of the working fluid can be used in the ORC system. In the literature study conducted by Bao and Zhao [6] about the review of the selection of working fluids used in the ORC system many criteria and types of working fluids can be used in ORC.
According to Moran et al. [7] the selection of working fluids to be used is generally based on 3 criteria including performance, safety, and factors on environmental impacts. The performance of the working fluid is based on the need for cooling or heat capacity and the cost of the operating system, the safety of the working fluid based on the content of hazardous substances in the working fluid such as toxic content and flammability, for the environmental impact of the working fluid based on the influence on the ozone layer or the effect on changes global climate. By analyzing the use of deeper fluids, the working fluid can be used as one of the optimization parameters to improve the performance of ORC [8].

ORC plants use biomass as an energy source to be one of the developments that have good potential. According to a literature study conducted by Rohmah et al. [9] stated that coconut shell is one of the potential biomass in Indonesia because it has an estimated production value of 9,548,000 tons/year with a heating value of 18.2 MJ / kg. In this study aims to determine the optimum parameters of the Organic Rankine Cycle power plant with R-134a working fluid sourced from coconut shell energy with test parameters namely the fuel rate and mass flow rate of work fluid, the optimum parameter determination is done by ORC performance simulation using software Cycle Tempo and for the properties of the R-134a working fluid are analyzed using REFPROP software.

2. Materials and methods

2.1. Data source
The data used are secondary data obtained from previous studies by Agtianisa [10]. This data is used as a basis for calculating the performance of the ORC generator using coconut shell and a source of refrigerant or working fluid heating in the simulation conducted. Data Performance of ORC generator using 2 testing parameters, such as: fuel rate of 2.5 kg/hour, 5 kg/hour, 7.5 kg/hour, and 10 kg/hour and mass flow rate of 1 GPM working fluid, 1.5 GPM and 2 GPM. Outgoing data of the condenser will be simulated for performance analysis using the cycle tempo software by first analyzing the R-134a working fluid property using the REFPROP software.

2.2. Components of simulation system development
The hardware used in this study was the Asus A455L laptop series with Intel Core i5 2.19 GHz-2.20 GHz processor and 4GB RAM. The programs used in this study were the Windows 10 operating system, Microsoft Excel 2016, Cycle Tempo software, and REFerence fluid PROPerties (REFPROP) software.

2.3. Research procedure
In this study, the analysis of thermal efficiency was carried out by using the Cycle Tempo software with the working fluid property of R-134a especially in the analysis that uses REFPROP software. The assumptions were based on the theory of heat transfer mass and energy of the Rankine cycle system; some of which are:

- Process 1 to 2: Compression of the working fluid at the pump
- Process 2 to 3: The heat that enters the system in the evaporator
- Process 3 to 4: Expansion of the turbine
- Process 4 to 1: Heat released from the system on the condenser
- The system that was simulated under steady-state conditions
- ORC system which was simulated in closed system condition
- Simulated performance data that was the most constant time-based temperature performance data of condenser outlet.

The optimum parameters of the study are set based on some optimum parameter criteria including:
- Having high thermal efficiency
- The quality of the working fluid at the evaporator exit is superheated, the quality of the working fluid at the exit expander is superheated, the quality of the working fluid at the condenser exit is subcooled, and the quality of the working fluid at the pump exit is subcooled.
- The outlet temperature and pressure of the expander must be higher than that of the pump inlet [11].

3. Results
The Organic Rankine Cycle (ORC) power system using coconut shell has 4 main components, such as: pump, evaporator, turbine, and condenser [12]. In the ORC generating system there were several supporting components such as boilers, coolant tubes, furnaces.

3.1. Analysis of working fluid property R-134a
Analysis Result of the working fluid R-134a using REFPROP software in the form of was an analysis of the working fluid phase condition that simulated at working temperatures and pressures. A pure substance that all have a permanent chemical composition was called a pure substance. Pure substance exists in various phases according to their energy level. A substance that was in the liquid phase but has not yet evaporated or is at a temperature below the boiling point is called a compressed liquid or a subcooled liquid. While the substance in the gas phase that has not been condensed is called superheated. In the liquid and gas mixture, the mass fraction of a fluid or substance is called the quality or ratio of the mass of the saturation of the gas and the mass of the saturation of the liquid. Quality has a value between 0 (liquid saturation) to 1 (gas saturation) [13]. The results of the analysis of the working fluid R-134a for all variations of the test parameters obtained the quality of the working fluid R-134a for T_{in} and P_{in} the pump are subcooled, T_{in} and P_{in} the evaporator are subcooled, Tin and Pin expander is superheated and for T_{out} and P_{out}, The expander are superheated.

3.2. Results of organic rankine cycle system performance using cycle tempo
3.2.1. Optimum parameters for mass flow rate variation. In the parameters of the coconut shell fuel rate shown in Figure 1, the highest thermal efficiency value was the fuel rate of 10 kg/hour, 5 kg/hour, 2.5 kg/hour, and 7.5 kg/hour respectively. For the fuel rate, the greater the fuel rate, the higher the heat generated by the furnace. Consequently, the temperature of the working fluid evaporation on the evaporator more higher, and of working fluid change more faster too.

![Figure 1](image_url)

**Figure 1.** The value of thermal efficiency to mass flow rate for variations in fuel rate.

According to Rohmah et al. [9], thermal efficiency increases with concomitant higher heat source temperatures. For the fuel rate of 7.5 kg / h has a thermal efficiency value of 6.02%, the thermal efficiency value was not much different from the 2.5 kg parameter which was 6.17%.
3.2.2. Optimum parameters for fuel rate variation. The optimum parameters for mass flow rate variations can be seen in Figure 2. It shows that the highest thermal efficiency values occur in the mass flow rate parameters of 2 GPM, 1 GPM, and 1.5 GPM respectively.

![Figure 2](image_url) The value of thermal efficiency on fuel rate with mass flow rate variations.

Effect of mass flow rate on ORC system performance, when the value of mass flow rate more greater so that the result of ORC performance more greater too, its caused, with a large mass flow rate value, there will be a large momentum between the working fluid and the turbine blade. Thermal efficiency was influenced by turbine work, pump work, and the rate of heat transfer in the evaporator. As heat from the evaporator and pump work was relatively constant with increasing turbine work along with increasing mass flow rate the efficiency will increase [14].

3.2.3. Organic Rankine Cycle (ORC) system performance for optimum parameters. Based on Figure 1 and Figure 2, it can be seen that the 3 parameter variations which have the highest thermal efficiency values in the mass flow rate and fuel rate parameter variations are the 10 kg/hour 2 GPM parameter variations with the thermal efficiency value of 13.7%, 5 kg/hour 1 GPM with the value of 8.48%, and 2.5 kg 2 GPM with a value of 6.17%.

![Figure 3](image_url) Results of ORC system temperature performance at fuel rates of 7.5 and 10 kg/hour.

The optimum parameter variation of 10 kg, 2 GPM at the expander outlet temperature has a lower value of 41,569 °C compared to the pump entry temperature of 62,305 °C. Figure 3 reveals the ideal state of the ORC system. The expander outlet temperature must be higher than that of the pump entry, and the pressure for the expander exit has the same value as the pump entry [11]. Based on the p-h diagram, for parameter variation of 10 kg/hour 2 GPM, it can be seen in figure 5 that in the ORC
system working cycle expander pressure was lower than the pump inlet pressure. Consequently 10 kg 2 GPM parameter variations could not be used as the optimum parameter.

Figure 4. Results of ORC system temperature performance at a fuel rate of 2.5 and 5 kg/hour.

The variation of parameters which has the second-highest thermal efficiency value was 5 kg/hour 1 GPM with a thermal efficiency value of 8.48%. In figure 5, it could be seen that the expander temperature has a higher value of 72.64 °C compared to the pump inlet temperature of 66.8 °C. For the requirement of the temperature at 5 kg/hour 1 GPM, parameter variation has suitable with the requirement. However, for the pressure on this variation, the parameter has a lower expander pressure value, compared to pump inlet pressure that can be seen in Figure 5. As a result, 5 kg/hour 1 GPM parameter variation could not be used as the optimum parameter because it did not match the ideal performance of the ORC system.

Figure 5. P-h diagram of the Organic Rankine Cycle system of working fluid R-134a (a parameter 10 kg/hour 2 GPM and (b parameter 5 kg/hour 1 GPM).

In the p-h diagram, there are 2 saturation lines, first liquid saturation line, and the second steam saturation line. The ideal cycle, four processes can be identified: 1) Isobaric evaporation, isobaric means that there is no pressure drop in the heat exchanger. Boilers can be divided into three zones: heating, evaporation, and superheating. 2) Adiabatic expansion (isentropic) where there is no heat in and out of the system, 3) Isobaric condensation, heat transfer can be divided into desuperheating, condensation, and subcooling zones, 4) Isentropic pump [11].
Figure 6. p-h diagram of the Organic Rankine Cycle system parameter 2.5 kg/hour 2 GPM.

The third highest thermal efficiency value was a parameter variation of 2.5 kg/hour 2 GPM. It could be seen in Figure 4 that the expander outlet temperature is 55,863 °C, while the pump inlet temperature is 40,265 °C. The expander pressure value was 14,275 bar, and the pump inlet pressure was 13.77 bar. Consequently, the parameter variation of 2.5 kg/hour 2 GPM suitable with the requirement because the temperature and pressure of the expander have a higher value than the pump inlet value. Based on the p-h diagram of the working fluid, the parameter variation of 2.5 kg/hour 2 GPM in Figure 6 (compared to the other 2 optimum parameters) was closer to ideal; because in process 1-2, the pump performs compression of the working fluid under isentropic conditions (or at constant enthalpy value), as well as processes 2-3 and 3-4 have the most ideal conditions. As a result, the optimum parameter in this study was a variation of the parameters of 2.5 kg/hour 2 GPM. This result was following the results of research [14] for example the highest mass flow rate has the highest efficiency value as well as 2 GPM in this study compared to the mass flow rate variation of 1 GPM and 1.5 GPM.

4. Conclusion
In this study, the optimum parameters were obtained for the performance of the Organic Rankine Cycle (ORC) generator using coconut shell with a laboratory-scale of 2.5 kg/hour for fuel rate and 2 GPM for mass flowrate with a thermal efficiency value of 6.17% and fulfilling the optimum parameter criteria.

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References
[1] Cengel Y A and Boles M 2015 Thermodynamics an Engineering Approach 8th Ed (New York (US): McGraw-Hill. International Edition)
[2] Pethurajan V, Sivan S and Joy G C 2018 Issues, comparisons, turbine selections and applications- An overview in organic rankine cycle Energy Conversion and Management 166 474-488
[3] Drescher U and Brüggemann D 2007 Fluid selection for Organic Rankine Cycle (ORC) in biomass power and heat plants Applied Thermal Engineering 27 223-228
[4] Chinese D, Meneghetti A and Nardi G 2004 Diffused introduction of organic rankine cycle for biomass-based power generation in an industrial district: a systems analysis International Journal of Energy Research 28 1003-1021
[5] Tchanche B F, Pétrissans M and Papadakis G 2014 Heat resources and organic rankine cycle machines. Renewable and Sustainable Energy Reviews 39 1185-1199
[6] Bao J and Zhao L 2013 A review of working fluid and expander selections for organic Rankine cycle Renew. Sustain. Energy Rev. 24 325–34

[7] Moran M J, Saphiro H N, Boettner D D and Bailey M B 2011 Fundamentals of Engineering Thermodynamics 7th Ed. (West Sussex (UK): John Willey & Sons Ltd.)

[8] Raghulanath D, Saravanan K, Mahendran J, Kumar M R and Lakshmanan P 2020 Analysis and optimization of organic rankine cycle for IC engine waste heat recovery. Material Today: Proceedings 21 30-35

[9] Rohmah N, Pikra G and Salim A 2013 Organic Rankine Cycle system preliminary design with corn cob biomass waste burning as heat source Energy Procedia 32 200-208

[10] Agtianisa N I 2019 Analisis Performansi Organic Rankine Cycle (ORC) dengan Sumber Panas Tempurung Kelapa dan Refrigerant R134a. [Paper]. Bogor (ID). Department of Mechanical Engineering and Biosystem. Faculty of Agricultural Technology Bogor Institute of Agriculture

[11] Quoilin S 2008 An introduction to Thermodynamics Applied to Organic Rankine Cycle (Cambridge (US): Massachusetts Institute of Technology)

[12] Tchanche B F, Loonis P, Pètrissans M and Ramenah H 2013 Organic rankine cycle systems principles, opportunities and challenges 25th International Conference on Microelectronics (ICM). 2013 Des 15-18; Beirut, Lebanon pp 296-299.

[13] Cengel Y A and Cimbala J M 2006 Fluid Mechanics Fundamental and Applications (New York (US): McGraw-Hill Companies, Inc.)

[14] Pamungkas A H and Putra A B K 2013 Studi variasi flowrate refrigerant pada sistem organic rankine cycle dengan fluida kerja R-123 Jurnal Teknik POMITS 2(2)