Efficiency analysis of refrigerant work fluid in the Organic Rankine Cycle (ORC) as an energy generating machine electricity 1 kW scale

M Y Abdullah*, P Prabowo and B Sudarmanta
Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

*muhamadyunus13@gmail.com

Abstract. At present, the depletion of fossil energy resources will have a significant impact on every aspect of life in Indonesia. One effort to overcome this problem is by conducting research to look for renewable energy sources. This study uses the Organic Rankine Cycle (ORC). The types of refrigerants used in this study are R141b, R245fa, and R123 using the Aspen plus Program Simulation. This study focuses on the working fluid R141b, R245fa, and R123 on the ORC as a 1 kW scale electric energy generator. The results obtained from the Aspen Plus Program Simulation in the ORC Cycle use working fluids R141b, R245fa, and R123 at a pressure of 3 bar to a pressure of 10 bar at a temperature of 95 °C. The maximum efficiency produced is 8.65%, 7.79%, and 8.36%. The turbine power produced is 1005 watts, 896 watts, and 770 watts. From the simulation results used in the ORC working fluid R 141b has an Efficiency and Power value that is best used as a 1 kW electric energy generator with an efficiency value of 8.65% and 1005 Watt Power.

1. Introduction
At present, the depletion of providing fossil energy sources will have a significant significance in every aspect of life in particular Indonesia and the world in general, to overcome the energy crisis, improve the environment and seek renewable energy sources [1-22]. Indonesia has abundant solar energy and geothermal energy that has not been utilized optimally. One solution to overcome the energy crisis problem is the use of sunlight energy, energy gas transfer, and geothermal energy using the Organic Rankine Cycle (ORC). The use of solar energy can be used by using a solar collector (PTSCS) with Organic Rankine Cycle (ORC) as an electric energy generator. [3]. Utilization of unused heat waste [7]. This is a source for utilizing heat that is not used as an energy source to produce electrical energy sources. In addition to exhaust gases, the factory can immediately bring environmental pollution gas. Refusing, relieving gas as soon as possible, can pollute the air in the form of gas and smoke. Gas and immediately are produced from the process of making incomplete fuels produced by factory machinery. In addition, the gas and smoke are the results of oxidation of various fuel constituent elements, namely: CO2 (carbon dioxide), CO (carbon monoxide), SOx (sulfur oxide) and NOx (nitrogen oxide). Acceptable above by agreeing to the Organic Rankine Cycle (ORC). This study discusses the analysis of working fluid efficiency by using the cycle of Organic Rankine Cycle (ORC) engine producing electricity with a capacity of 1 kW. One of the efforts expected in this study by using liquids that work in the Organic Rankine Cycle (ORC) can be used as a 1 kW electric generator.
2. ORC system design and work fluids
The design in this study uses the Aspen Plus program with working fluids R-141b, R-123, and R-245fa by calculating the maximum power and efficiency produced. Organic Rankine Cycle (ORC) is a very simple type of cycle that uses Refrigerant as its working fluid. By using Refrigerant materials that have a large molecular mass with a low boiling point compared to the boiling point of water. This liquid makes it possible to work at low temperatures with the Organic Rankine Cycle. Heat sources that are not used are used or waste from industry (waste heat), geothermal (Geothermal), solar heat (solar cells) and so on can be used as an energy source. The heat can be converted into Power in a turbine by connecting to a generator and converted into electrical energy. The ORC cycle is a simple steam cycle in which this cycle uses Refrigerant as a working fluid. In this study, the Organic Rankine Cycle (ORC) cycle using the Aspen Plus Program is shown in Figure 1 below:

![Figure 1. Organic Rankine Cycle (ORC) scheme using the aspen plus program.](image)

Early operational standards used the Aspen Plus software. Research using the Aspen Plus program is very helpful before being carried out experimentally to select the best working fluid material in the study experimentally. The work fluids carried out in this study are Refrigerants R141 b, R123, and R245 fa.

In this study to analyze the efficiency and working fluid power of the Organic Rankine Cycle (ORC) as an electric energy generator, calculations were made from the results of testing observations. Energy analysis on each of the main components of the Organic Rankine Cycle system can use the first legal equation of thermodynamics to get the work of output and heat received or issued by this system.

2.1. Process 1 - 2 (Turbine)
Steam from the evaporator at point 1. With high temperatures and pressures, entering the turbine is then expanded to enter the condenser at point 2. By taking volume control on the turbine and assuring that the turbine is working isentropically, then turbine power can be calculated by the following equation:

\[ W_T = \dot{m} (h_1 - h_2) \]  

Where \( W_T \) is a power turbine, for \( h_1 \) and \( h_2 \) is the enthalpy of the working fluid that enters and leaves the turbine.

2.2. Process 2 - 3 (Condenser)
For processes 2 - 3 occurring in the condenser, the heat lost to the condenser can be determined by the equation:

\[ Q_c = \dot{m} (h_2 - h_3) \]  

Where \( h_2 \) and \( h_3 \) are enthalpies of the working fluid that enters and exits the condenser.
2.3. **Process 3 - 4 (Pump)**

Refrigerant comes out of the condenser at point 3 then is pumped towards the evaporator. By taking the volume control at the pump and assuming that the pump works isentropically, pump power can be calculated by the following equation:

\[ W_p = \dot{m} (h_4 - h_3) \]  

Where \( W_p \) is the work of the pump, for \( h_3 \) and \( h_4 \), it is the enthalpy of the working fluid entering and exiting the pump that works isentropically.

2.4. **Process 4 - 1 (Evaporator)**

For processes 4 - 1 occur in the evaporator where an evaporation process occurs to convert the liquid into steam, where the average heat given by the evaporator to the working fluid can be determined by the equation:

\[ W_e = \dot{m} (h_1 - h_4) \]  

Where \( h_1 \) and \( h_4 \) are enthalpies of the working fluid that comes out and enters the evaporator.

2.5. **Cycle Efficiency:** For efficiency of the cycle can be stated

For cycle, efficiency can be announced as the ratio between the network cycles divided by the heat given by the evaporator can be written as follows:

\[ \eta_{cycle} = \frac{\dot{W}_e}{\dot{Q}_c} \]  

3. **Results and analysis**

3.1. **Turbine power analysis of pressure at temperature 95 °C**

Analysis of working fluid power R 141 b; R 245 fa; R 123 at a pressure of 0 to 10 bars at temperature 95°C.

A mixture of zeotropic substance can increase the working fluid [2] In Figure 2 based on the working fluid graph R 141 b, R 245 fa, and R 123 maximum peak Power at pressure 6 bar R 141 b, R 245fa and R 123 is 1005 watts, 896 watts, 770 watts. The duration of injection of working fluid R 141 b has better power compared to refrigerant R 245 fa and R 123. This is because of the higher the pressure of the turbine, the greater the working fluid that enters the turbine chamber and higher flow turbulence which causes mixing of the coolant better or more homogeneous. With a homogeneous mixture of refrigerants, the pressure process will take place higher, when turbine pressure is reduced, losses due to friction (loss of friction) on the turbine are also reduced so that the amount of power used to compensate for losses. In addition, the higher the turbine pressure, the playback time will take place faster so it is possible for the working fluid not to compress.
3.2. **Evaporator analysis with pressure at temperature 95°C**

Analysis of evaporator to produce further heat vapor at working fluid R141 b; R 245 fa and R 123 at 95°C at a pressure of 3 bars to 11 bars.

![Graph relationship between power evaporator and pressure at temperature 95°C.](image)

*Figure 3. Graph relationship between power evaporator and pressure at temperature 95°C.*

Increasing the Qalor in the evaporator can reduce the pressure and the liquid becomes superheat [4]. In figure 3 shows the results of testing the refrigerant using the working fluid R 141 b, R 245 fa, R 123 carried out at a pressure of 0 to 10 bars. From the test results can be seen from Figure 3 graph the relationship between Pressure and Qalor shows a decrease in Qalor which is produced together with a decrease in pressure on the evaporator. Of the three working fluids shown in the Qalor graph the maximum is R 141b, R 245fa and R 123 are 11480 watts, 11360 watts, 9091 watts. The steam equation produced by R 141b is better than R 245fa and R 123. From the simulation results using a program where R 141 b has better enthalpy than R 245 fa and R 123. The simulation results using reprof are shown in Figure 4.

![Relationship between the pressure graph and enthalpy using the reprof program.](image)

*Figure 4. Relationship between the pressure graph and enthalpy using the reprof program.*

The working fluid in Organic Rankine Cycle (ORC) is an important part of an energy generator to produce power to rotate turbines [7]. This is due to the duration of heat generated in the Evaporator on the Rankine Cycle Organic Cycle system depending on the ability or warm-up time to produce further steam. The heat duration of refrigerants in the Organic Rankine Cycle is carried out in order to obtain a more appropriate amount of refrigerant to be inserted into the turbine. So that in setting the injection duration is adjusted to the characteristics possessed by the refrigerant to drive the turbine. From the duration of heat generated at the evaporator where the working fluid R 141b is better used to rotate the turbine than the refrigerant R 245fa and R 123.

3.3. **Pump power analysis with pressure at temperature 95 °C**

Pump power analysis in Figure. using working fluids R 141 b, R 245 fa and R 123 at a pressure of 0 to 10 bar at a temperature of 95°C.
Figure 5. Graph of the relationship between pump power and pressure at temperature 95 ºC.

In the picture. The maximum power of the refrigerant pump R 141b, R 245fa, and R 123 are 12 watts, 11 watts, and 10 watts at a pressure of 5 bar and a temperature of 95 ºC. The increase in pump power that occurs in the use of refrigerants is caused by the flame speed possessed by R 141b refrigerant is much better, causing pumping from the condenser to the evaporator to be faster because the pressure produced by refrigerant R 141b is more optimal than refrigerant R 245 fa and R 123.

3.4. Analysis power condenser analysis with pressure at temperature 95ºC

Condenser Analysis in figure 6 using working fluids R 141 b, R 245 fa and R 123 at a pressure of 10 bar with a Temperature of 95.

Figure 6. The relationship between condenser power and pressure at a temperature of 95ºC.

Steam-quality cooling water temperature Y. Yuan [5] In Figure 6 of the three working fluids used graph R 141b requires cooling that is greater than R 245 fa and R 123. This is because the Cooling Duration produced on the Condenser on the Rankine Organic Cycle system depends on the ability or cooling time coming out of the Turbine to cool the fluid work on the condenser. Changing the characteristics of the working fluid in gas into a change in the liquid phase is very important for pumping the working fluid into the evaporator. So that in adjusting the duration of the refrigerant injection cooler as much as possible adjusted to the characteristics possessed by the refrigerant to be pumped into the evaporator. From the duration of cooling, heat is generated on the condenser at a temperature of 95 º C working fluid R 141 b, R245fa, and R123. The heat energy produced is 10487 watts, 10475 watts, and 8331 watts so that R 141b used requires more energy to cool the working fluid than R245 and R123 refrigerants.

3.5. Thermal efficiency analysis at a pressure of 5 bars with a temperature of 95ºC

The value of thermal efficiency (ƞth) of coolant R 141b, R 245 fa and R 123 with a working fluid rate of 0.04719 kg/s is shown in the figure below this:
Figure 7. Graph of the relationship between thermal efficiency (%) and pressure at temperature 95ºC.

The duration of heat generated in an Evaporator at Organic Rankine Cycle depends on the ability or time to produce superheat [22]. In Figure 7 above shows a graph of thermal efficiency and pressure. In general, the graphs of testing R 141 b, R 245 fa, and R 123 show the same trend. But the thermal efficiency of R 141 b has better thermal efficiency than R 245fa and R 123. When the high pressure of the working fluid is not optimal, the power that occurs is less than perfect. At the optimal point of working fluid turbulence and working fluid pressure, it reaches the best conditions so as to obtain the highest efficiency. Along with the addition of refrigerant to the turbine that is too high, the turbulence that occurs is quite large, so that the working fluid needed is better, but when high temperatures occur, the turbine turns so fast that there is a part of the cooling working liquid that is wasted. For this reason, it is necessary to add a Recuperator to increase efficiency so that the working fluid Refrigerant that is not used at a certain temperature can be utilized.

4. Conclusion

The conclusions that can be drawn from this study are:

- Research requires a large budget using the Aspen Plus program to help research experimentally.
- The ORC research can utilize waste heat, exhaust gas heat sources that can be renewed, solve the problem of CO2 emissions, air pollution, environmental pollution and overcome the crisis of global warming.
- The maximum efficiency produced is R 141b, R 245fa and R 123 is 8.65 %, 7.79 % and 8.36 %. The maximum power is 1005 Watts, 896 Watts, and 770 watts. From the experiment, R 141b has an Efficiency and Power value that is best used as a 1 kW electric energy generator.

Acknowledgements

The author would like to express his gratitude for the support of the Ten November Institute of Technology Lecturer, the Sepuluh Nopember Institute of Technology Research Center, the Naval Education Office which has provided opportunities and funding support to study at the Sepuluh Nopember Institute of Technology Surabaya.

References

[1] S Lia, C N Michosa, I Vlaskosa, C Rouaudb, R Taccanich 2017A review of waste heat recovery and Organic Rankine Cycles (ORC) in on-off highway vehicle Heavy Duty Diesel Engine applications International Journal, Renewable and Sustainable Energy Reviews 79 691–708.
[2] G B Abadi and K C Kim 2017 Investigation of organic Rankine cycles with zeotropic mixtures as a working fluid: Advantages and issues International Journal, Renewable and Sustainable Energy Reviews 73 1000–1013.
[3] A Erdogan, C O Colpan and D M Cakici 2017 Thermal design and analysis of a shell and tube heat exchanger integrating a geothermal-based organic Rankine cycle and parabolic trough
solar collectors International Journal, Renewable Energy 109 372e391.

[4] A Desideri, J Zhang, M R Kærn, T S Ommen, J Wronska, V Lemort and F Haglind 2017 An experimental analysis of flow boiling and pressure drop in a brazed plate heat exchanger for organic Rankine cycle power systems International Journal of Heat and Mass Transfer 113 6–21.

[5] Y Yuan, G Xu, Y Quan, H Wub, G Song, W Gong and X Luo 2017 Performance analysis of a new deep super-cooling two-stage organic Rankine cycle International Journal, Energy Conversion and Management 148 305–316.

[6] G Shu, P Liu, H Tian, X Wang and D Jing 2017 Operational profile-based thermal-economic analysis on an Organic Rankine cycle using for harvesting marine engine’s exhaust waste heat International Journal, Energy Conversion and Management 146 107–123.

[7] A M A Jubori, R Al-Dadah and S Mahmoud 2017 An innovative small-scale two-stage axial turbine for low-temperature organic Rankine cycle International Journal, Energy Conversion and Management 144 18–33.

[8] S C K De Schepper, G J Heynderickx and G B Marin 2009 Modeling the evaporation of a hydrocarbon feedstock in the convection section of a steam cracker Computers and Chemical Engineering 33 122-132.

[9] H L Wu, X F Peng, P Yea and Y E Gong 2007 Simulation of refrigerant flow boiling in serpentine tubes International Journal of Heat and Mass Transfer 50 1186–1195.

[10] K Sung-Min and I Mudawar 2013 Universal Approach to predicting saturated flow boiling heat transfer in mini/micro-channels Part I. Dryout incipience quality International Journal of Heat and Mass Transfer 64 1226-1238.

[11] B K Hardik, G Kumar and S V Prabhu 2017 Boiling pressure drop, local heat transfer distribution and critical heat flux in horizontal straight tubes International Journal of Heat and Mass Transfer 113 466–481.

[12] W Chi-Chuan, I Y Chen and H Pi-Shan 2005 Two-phase slug flow across small diameter tubes with the presence of vertical return bend International Journal of Heat and Mass Transfer 48 2342-2346.

[13] A Erdogan, C O Colpan and D M Cakici 2017 Thermal design and analysis of a shell and tube heat exchanger integrating a geothermal-based organic Rankine cycle and parabolic trough solar collectors Renewable Energy 109 372e391.

[14] Y A Cengel Heat Transfer A Practical Approach, Second Edition

[15] J Yu, H Mab and Y Jiang 2017 A numerical study of heat transfer and pressure Drop of hydrocarbon mixture refrigerant during boiling in vertical rectangular omnichannel available ScienceDirect Applied Thermal Engineer 12 1343 – 1352.

[16] L Liu, T Zhu and J Ma 2017 Working fluid charge oriented off-design modeling of a small scale Organic Rankine Cycle system International Journal, Energy Conversion and Management 148 944–953.

[17] L V Han, J Wei-ting and Z Q Zhi 2015 Organic Rankine cycle simulation based on Aspen Plus Advanced Materials Research 1070-1072 1808-1811.

[18] A Rahman, M G Rasul, M M K Khan and S Sharma 2014 Aspen Plus based simulation for energy recovery from waste to utilize in cement plant preheater tower International Journal, Energy Procedia 61 922 – 927.

[19] W Lan, G Chen, X Zhu, X Wang, C Liu and B Xu 2018 Biomass Gasification-gas turbine combustion for power generation system model based on ASPEN PLUS Contents lists available at ScienceDirect, Science of the Total Environment 628–629 1278–1286.

[20] G Cavallaglio, V Coccia, F Cortana, M Gelosia, A Nicolini and A Petrozzi 2018 Energy from poultry waste: An Aspen Plus-based approach to the thermo-chemical processes Contents lists available at ScienceDirect, Waste Management 73 496–503.

[21] Organic Rankine cycle simulation based on Aspen Plus 2015 Advanced Materials Research 1070-1072 1808-1811.
[22] J Shi, G Zheng and Z Chen 2018 Experimental investigation on flow condensation in horizontal tubes filled with annular metal foam *International Journal of Heat and Mass Transfer* 116 920–930A.