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Evaluation of Three Working Fluid on an Organic Rankine Cycle of a Waste Heat Recovery Electric Generator

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Abstract: The aim of this study is to evaluating an Organic Rankine Cycle (ORC) system from diesel engine waste heat recovery by selecting three different working fluids with different pressure and temperature condition. The working fluid include N-Pentane, R-245fa, and R-134a are conditioned on variations in pressure and evaporation temperature with a difference of 0.5 bar and 5 °C to achieve the best thermal efficiency. The proposed evaluation involved two phases, first is analysis of the working fluid with various condition is carried out using REFPROP software and then results of that analysis will be used as the basis of input in calculating the overall heat balance using the Cycle Tempo software. This study found that a diesel engine with a capacity of 1000 kVA wastes energy of 1177 kW which is released through exhaust pipe and engine radiator can produce a turbine power of 144,47 kW. The highest thermal efficiency of 13.48% was obtained by using the working fluid R-245fa at the evaporator pressure and temperature of 23.5 bar and 154 ºC, respectively.

Keywords: Organic Rankine Cycle, thermal efficiency, waste heat recovery, working fluids

1. Introduction

Electrical energy is one of the basic needs in daily life where almost all human activities are related to electrical energy. Economic growth is increasing which is noticed by the development of the industrial sector like manufacturing,

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construction, services, and so on, which requires electrical energy to carry out its operational activities. Moreover, the population is also currently showing an increase every year and of course the need for electrical energy will also increase. Generally, energy sources in Indonesia come from fossil fuels such as oil and coal, which are limited in availability and the commitment of countries in the world to reduce greenhouse gas emissions because this is a serious threat to the environment also a challenge [1] - [3]. To reduce air pollution and global warming as a result of burning fossil fuels, it can be done by using renewable energy that is more environmentally friendly or by utilizing waste heat from the combustion of fossil fuels [4]. Waste heat recovery from fossil fuel power generator become crucial since approximately 50% from used energy are wasted in vain due to limitation of energy conversion process [5], [6]. One of the ways to recovering this exhaust gas is to apply the ORC system.

The ORC is a Rankine Cycle that uses refrigerant as its working fluid instead of water. The advantage of the ORC system compared to other generating systems is more economical because it does not require fuel, low maintenance costs, and automatic operation, also it does not cause air pollution that harms the environment [7] - [9]. For an office area with four to five storey buildings and a total of 1000 employees, generator with capacity of 2 x 1000 kVA is required. With a generator of that size, the ORC system can be applied to get additional electrical energy that can be used and of course environmentally friendly.

Previous research studied the optimization of the evaporator and condenser components of the existing ORC system to obtain optimum performance [10]. Therefore, this study will be designing overall system from 1000 kVA diesel engine waste heat and then the three of working fluids will be compared to get the best efficiency from the system which will be designed according to the waste heat characteristics of the diesel engine. The best efficiency will be obtained by conducting research on the variables that affect the quality of the working fluid such as the temperature of the evaporator heater and the pressure of the working fluid in the system, so that system optimization can be achieved.

Tuan, Anh (2018) explains about waste heat recovery from engine diesel with ORC system. The condition of waste heat becomes crucial for calculating and designing an ORC system. The temperature of exhaust gas and its mass flow are the most major parameters. Environmental influences should also receive more attention in selecting the working fluid, such as the value of Ozone Depletion Potential (ODP) must be below 0.2 and the value of Global Warming Potential (GWP) must be lower than 1500 [11].

Bao, Junjiang and Zhao, Li (2013) explains that the performance of the ORC system is strongly depends on working fluid's properties used which can have an impact on system efficiency, operating conditions, environmental impact, and economic sustainability. This following characteristic of working fluid properties which affects the system efficiency and thermodynamic performance; Vaporization latent heat, density, specific heat, critical temperature, boiling temperature, freezing point, molecular weight, molecular complexity, viscosity, and conductivity [12] - [15].

There is also another study that explains the utilization of waste heat from the exhaust gas of a steam power plant with a capacity of 400 MW with an exhaust gas temperature of around 150 °C which can generate 1 MW electricity with an ORC system. Working fluids used in that study are R-12, R-134a, and R-152a. From these studies resulted that the choice of refrigerant as a working fluid must be adjusted to the thermodynamic characteristics which include, evaporation temperature and vaporization pressure as well as condensation temperature and condensation pressure [16].

Fluid selection must be based on thermodynamic, environmental, and economic criteria such as efficiency, non-flammability, low toxic, zero ozone depletion potential and low costs to obtain high efficiency while maintaining engine and environmental safety. Previous studies have simulated with optimization comparisons for 8 working fluids, namely HFE7000, HFE7100, PF5050, R123, n-pentane, R245fa, R134a and Isobutane, where this simulation is shown for heat sources from the sun, earth, biomass, and recovery from waste heat (waste heat). The results of the study were in the form of an efficiency arrangement based on the spinal point method, from the highest to n-pentane, R245fa, R134a. While the order of efficiency put forward by other researchers mentions the highest efficiency in a row are: R245fa, n-pentane, R134a [17]. With the difference in the characteristics of the exhaust heat used, the working fluid used will also be different. It could be that the working fluid R-134a is suitable for ORC with solar heating or R-245fa produces the best performance on ORC with geothermal as its heat source. By considering the ease of obtaining it and the environmental impact, in this research the working fluid to be studied is n-Pentane, R-134a, and R-245fa.

2. Heat Recovery System

The best energy is energy that is not used, this statement is the basis of the concept of utilizing heat [18]. The basic concept of heat recovery is heat that created by the results straight from any engineering process or second process are utilized. The common application of electric generator at the moment has roughly around 70% efficiency, that means more than one third of total energy input is wasted through exhaust pipe and cooling system [19] - [21]. In some machine that generates heat on the process such as boilers, ovens, and internal combustion engine are releasing exhaust gases at very high temperature, which is a useful energy source that can be used to reducing energy consumption. According to equipment used, application, exhaust gases temperature, and recovery purpose are the classification of how the heat from exhaust gas are utilized. Exhaust gas utilization can be used as heat storage, heating, electricity generation, and cooling depending on the needs [22].

An Organic Rankine Cycle is an environmentally friendly system, this system utilized low-quality heat source. Assembled with four main components, evaporator, turbine, condenser, and pump that uses organic substance as its working fluid. The advantages of this system are that the size is not too large, there are no exhaust emissions such as CO, CO2, NOX, and other pollutants. Evaporator will evaporate working fluid that turn it into gas with high pressure. Then the gas will be converted into low pressure through the turbine. High pressure gas rotates the blade inside the turbine and converted into mechanical energy that can be used to generate electricity using a generator. The output gas form turbine released its remaining heat to environment on condenser so the phase return into liquid before enter the pump. In the ORC system, the turbine used is a hermetic type turbine to prevent fluid leakage [23] - [25].

The aim of this study is to achieve the highest efficiency that can be applied to 1000 kVA diesel engine. Initial data is needed from each working fluid which is used as a best practice to optimize. That data parameter was obtained from existing ORC system, namely from one of the geothermal power plants in Indonesia where the working fluid used is n-Pentane with the highest working efficiency obtained when the temperature and evaporation pressure are at 117 °C and 9 bar. The information of R-245fa' highest efficiency can be found from the product specifications issued by one of the ORC engine manufacturers. From the specification data, it is known that the ORC engine that uses R-245fa has the greatest efficiency when the evaporation temperature is 144 °C with a pressure of 24.5 bar. Then for R-134a, it was obtained from a literature study where in a study it was said that at the evaporation temperature and pressure of 85 °C and 17 had an efficiency of 6.19% [26]. The maximum value of heat-recovery efficiency can be obtained by adjusting the evaporation temperature and condensing temperature. In addition, efficiency can also increase if the exhaust heat temperature increases and can decrease when using a working fluid with a lower critical temperature [27].

3. Methods

Fig. 1 shows the flowchart of the process for optimizing ORC system from the utilization of waste heat by comparing the working fluids. Starting from the initial analysis of waste heat data from the exhaust gas, analyzing the working fluid when given the designed working pressure and temperature, and then performing calculations and optimization so that the highest efficiency can be achieved.

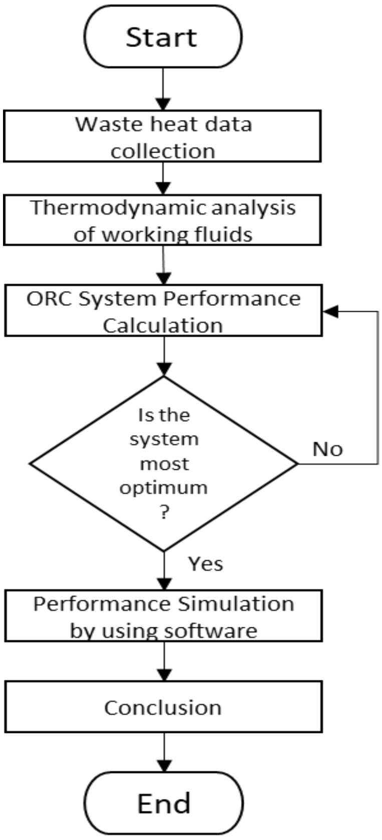


Fig. 1 - Flowchart of research method

3.1 Working Fluid Analytic

Properties of the fluid are affected by the characteristic of received temperature in evaporator, a comparison must be analyzed between the three working fluids. The fluid analysis process must be carried out to ensure that the phase of the working fluid from the evaporator output or turbine input is superheated, and the working fluid phase is subcooled when entering the pump. The state of the working fluid phase can be known by determining the temperature and pressure variables in each evaporation and condensation process. This fluid analysis was performed using REFPROP software. In addition, the pressure of the working fluid in the system will also influence the quality of the fluid which of course will have an impact on thermal efficiency.

The analysis conducted by giving some condition at highest efficiency in each working fluid that applied to other working fluid, which means the given evaporation temperature are 144 °C, 126 °C, 85 °C. And evaporation pressure at 24.7 bar, 17, bar, an 9.5 bar. By using the REFPROP software, it was found that when R-134a given to all variables of temperature and pressure conditions, the phase was superheated. For fluid R-245fa, the fluid condition is superheated if it operates at a temperature of 144 C and at all pressure variables. It's just that when operating at an evaporation temperature of 85 °C, the fluid phase becomes subcooled. And at the temperature of 126 °C, only when the pressure is 24.5 bar the fluid phase becomes subcooled, the rest is in a superheated condition. As for n-pentane, the fluid phase will be in a superheated state if the fluid operates at a pressure of 9.5 bar with a temperature of 144 °C and 126 °C, and the rest when conditioned with other variables is still in a subcooled state. If the working fluid phase entering the turbine is subcooled, the system will not work because to be able to rotate the turbine, the working fluid phase must be in a state of steam or hot steam. For this reason, simulations with variables that make the turbine input working fluid phase subcooled cannot be carried out.

The critical temperature of n-Pentane is 195.85 C the highest critical temperature. Then for R-245fa, the critical temperature of this working fluid is 153.85 C. While the working fluid with the lowest critical temperature is R-134a, which is 101.06 C [28]. Hence, the adjusting of evaporation pressure and temperature to find the highest efficiency can't compare with other working fluids the highest efficiency's condition.

Three working fluids which are n-Pentane, R-245fa, and R-134a conditioned on variations in pressure and evaporation temperature with a difference of 0.5 bar and 5 °C from the previous best practice with expectation that optimization is still possible.

Table 1 - Design condition for each working fluid

Optimization for R-245fa		**Optimization for n-pentane**		**Optimization for R-134a**	
Temperature (^{0}C)	**Pressure (bar)**	**Temperature (^{0}C)**	**Pressure (bar)**	**Temperature (^{0}C)**	**Pressure (bar)**
154	25.5	136	10.5	95	18
149	25	131	10	90	17.5
144	24.5	126	9.5	85	17
139	24	121	9	80	16.5
134	23.5	-	8.5	75	16

3.2 Simulation Procedure

Cycle Tempo software is an application for the design, optimization and operation of energy systems and their components. By using a more sophisticated model, making the calculation results more accurate. The exhaust heat from the exhaust gas does not directly heat the ORC evaporator, but the energy will be transferred first through the water medium. By applying hot water circulation as a heat exchanger medium to integrate the exhaust heat from the diesel engine with ORC, it will create the best heat exchanger network (HEN) configuration which can maximize the utilization of exhaust gases from the diesel engine combustion process [29]. The heat source from the jacket water engine is utilized as a preheater before the evaporator in order to get maximum thermal efficiency. An ORC design of the Cycle Tempo software is shown in Fig. 2.

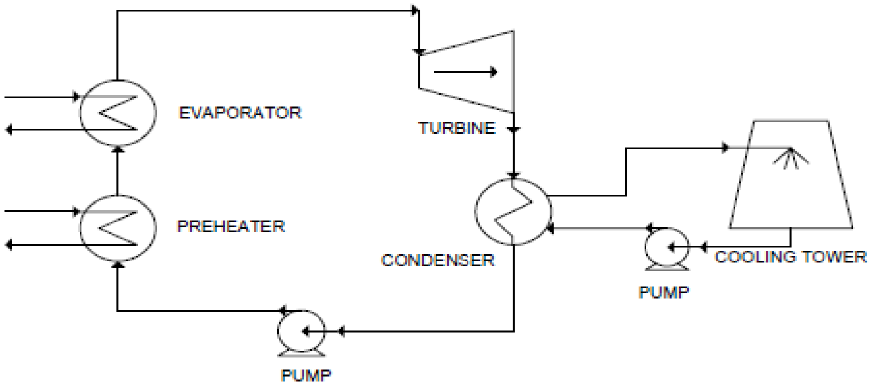


Fig. 2 - ORC schematic diagram

However, to perform simulations using Cycle-Tempo software, it is necessary to set conditions like regulating the efficiency of pumps and turbines as well and other parameters needed for the system to work. This simulation must meet several conditions and restrictions as follows:

- The working fluid output of the evaporator and turbine is superheated.
- The pump output working fluid is in a liquid state.
- The process that takes place in the condenser and evaporator is isobaric.
- Turbine efficiency by 80%.
- Pump efficiency by 75%.
- The decrease in pressure and temperature in the turbine adjusts to best practice.
- Condensation temperature according to best practice.

4. Results and Discussion

4.1 Waste Heat Energy Available

The heat wasted from exhaust gas of a diesel engine can be found using equation below:

$$Q = \dot{m}_{eg} \cdot c_p \cdot \Delta T \qquad (1)$$

The mass flow rate of the exhaust gas ($\dot{m}_{eg}$) is obtained from:

$$\dot{m}_{eg} = \dot{m}_f + \dot{m}_a \qquad (2)$$

And for the usable net power output are the power that generated from generator deducted by the power to operate the ORC system, which is pump power.

$$W_{ORC,\, net} = W_t - W_p \qquad (3)$$

From the simulation above, thermal efficiency of the ORC system can be determined by following equation.

$$\eta = \frac{W_t - W_p}{Q_{in}} \qquad (4)$$

Where $\dot{m}_f$ are mass flow rate of fuel used and $\dot{m}_a$ are the mass flow rate of air in the exhaust pipe [30]. The diesel engine used in this study consumes 249 liters of fuel per hour in Standby Power mode, 224 liters per day in Prime Power mode, and 155 liters per day in Continuous Base load mode. So, then the mass flow can be calculated by multiplying fuel consumption by the density of diesel fuel. The manufacture of the diesel engine used in this study has issued a technical data sheet which contains very complete information. From the data that has been provided which of course has gone through more comprehensive research, the energy balance of every process that occurs in the diesel engine can be found. The maximum energy potential of exhaust gas that can be utilized is 811 kW. Then to find the mass flow rate of air that enters the combustion chamber, it is necessary to know the specifications of the engine used for this research. The diesel engine used is an engine with bore and stroke sizes of 160 mm and 190 mm, respectively. With a total of eight cylinders and a four strokes cycle. While the speed of this diesel engine is 1800 RPM.

Table 2 - Energy designation from diesel engine

Designation	Units	Continuous baseload	Prime power	Stanby power
Energy in fuel	kWt	1738	2250	2516
Energy in power output (gross)	kWb	715	894	980
Energy to cooling fan	kWm	56	56	56
Energy in power output (net)	kWt	659	838	924
Energy to exhaust	kWt	550	725	811
Energy to coolant and oil	kWt	255	336	366
Energy to radiation	kWt	59	85	100
Energy in to charge coolers	kWt	160	210	259

(Source: compiled by the author from the engine manufacturer data sheet, 2021)

According to the data that obtained from the manufacturer of the diesel engine, it can be seen that the energy wasted in vain through exhaust gases is around 32% of the maximum energy that can be produced by fuel as shown in table 2. It also stated that there another wasted heat can be recovered which is heat from jacket water that has energy of maximum 366 kW. This waste heat form jacket water through coolant and oil can be used for pre-heater to make system efficiency higher. The temperature of brine water is set at 167 °C, 7.4 bar, and mass flow rate at 15 kg/s. And for the pre-heater, the water temperature will be 87 °C, 1.6 bar, and 13.75 kg/s mass flow.

4.2 ORC System Performance Calculation

Simulating the ORC model will be very useful for optimizing operating conditions and system components because by doing simulations, calculations can be made to achieve improvements [31].

Based on best practice from the actual reference existing ORC system using n-Pentane as the working fluid, it was found that the turbine output temperature and pressure were 95.5 °C and 1.41 bar. Furthermore, the mass flow rate is determined at 1.766 kg/s. N-Pentane as the working fluid used for utilizing a 1000 kVa diesel engine waste heat achieve the highest efficiency at 11.38%. The highest thermal efficiency is obtained when the system uses an evaporation pressure and temperature of 16 bar and 136 °C.

Next, to determine the turbine output temperature and pressure for R-245fa simulation, in this study using a reference from the ORC engine product specification from one product with a capacity of 140 kW. In this engine, the output pressure and temperature of the turbine used are 3.2 bar and 82.5 C. The simulated mass flow rate is 3.606 kg/s. Simulation with R25fa can achieve the highest thermal efficiency of 13.48%. The highest thermal efficiency is obtained when the system uses an evaporation pressure and temperature of 23.5 bar and 154 °C.

And for R-134a, it was found that the turbine output pressure and temperature were 6.5 bar and 65 C. The simulated mass flow rate is 5.2 kg/s. From the simulation using R-134a as the working fluid, it is found that the system can achieve the highest efficiency of 9.32%. The highest efficiency was obtained at the pressure and temperature evaporation conditions of 8.5 bar and 96 °C.

4.3 Performance Simulation by Using R245-fa

The results of the analysis will be used as the basis of input in calculating the overall heat balance using the Cycle Tempo software so can conduct a flow sheeting for the thermodynamic analysis and optimization of energy conversion systems. Cycle tempo simulation using R245fa is shown in Fig. 3.

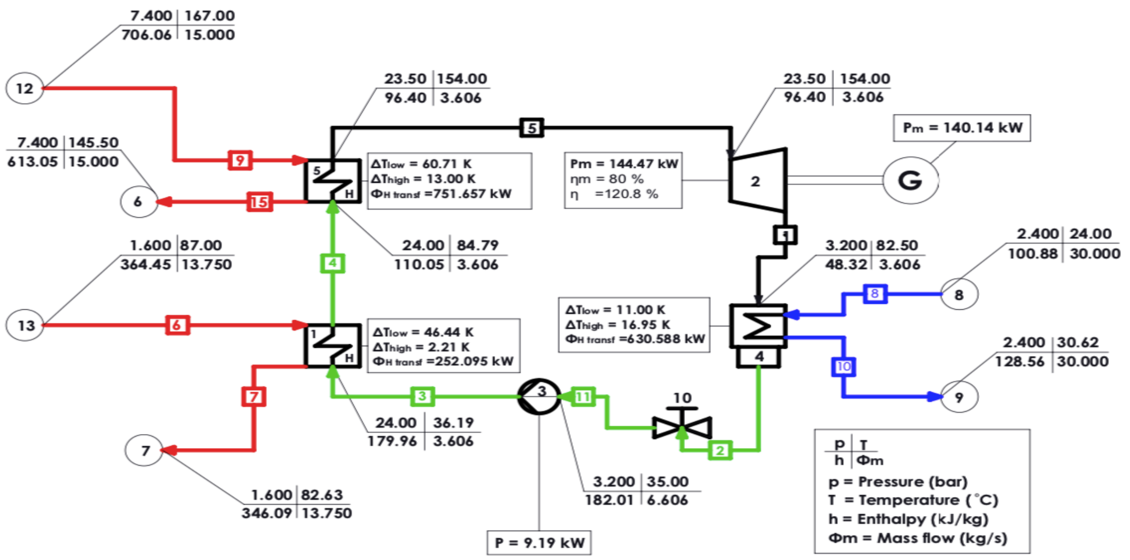


Fig. 3 - Cycle tempo simulation using R245fa

The Fig. 4 shows the characteristic Q-T diagram of the evaporator. The line indicates how two different fluids transferring heat from each other affecting its temperature. There will be exergy destruction in heat transfer process and this diagram shows how much exergy destruction occurred in the process. The more contiguous the line are, the less exergy destruction. Pinch point which is defined as the lowest point when heat transfer between the two streams (hot and cold) occurs showed by the closest point between two lines. The heat transfer around the critical point is very important information to analyze the heat transfer mechanism in the evaporator [32].

Exergy available on the hot fluid (exhaust gas and jacket water)

$$Ex_{H,in} = \left[\left(h_{H,in} - h_o\right) - T_o\left(s_{H,in} - s_o\right)\right] * m_{H,in} \tag{5}$$

Exergy lost in exhaust gas

$$Ex_{H,out} = \left[\left(h_{H,out} - h_o\right) - T_o\left(s_{H,out} - s_o\right)\right] * m_{H,out} \tag{6}$$

Exergy is absorbed by refrigerant R-245fa (cold fluid)

$$Ex_C = \left\{ \left[\left(h_{c,out} - h_o\right) - T_o\left(s_{C,out} - s_o\right)\right] - \left[\left(h_{c,in} - h_o\right) - T_o\left(s_{C,in} - s_o\right)\right] \right\} * m_C \tag{7}$$

Exergy lost

$$Ex,_{loss} = Ex_{H,in} - Ex_{H,out} - Ex_C \tag{8}$$

Exergy efficiency

$$\eta_{Ex} = \frac{Exergy\ avaibility - Exergy\ loss}{Exergy\ avaibility}$$

$$Ex = \frac{Ex_{H,in} - Ex_{H,out}}{Ex_{H,in}} \tag{9}$$

$$\phi_H = U.\ A.\ \Delta T_{ln} \tag{10}$$

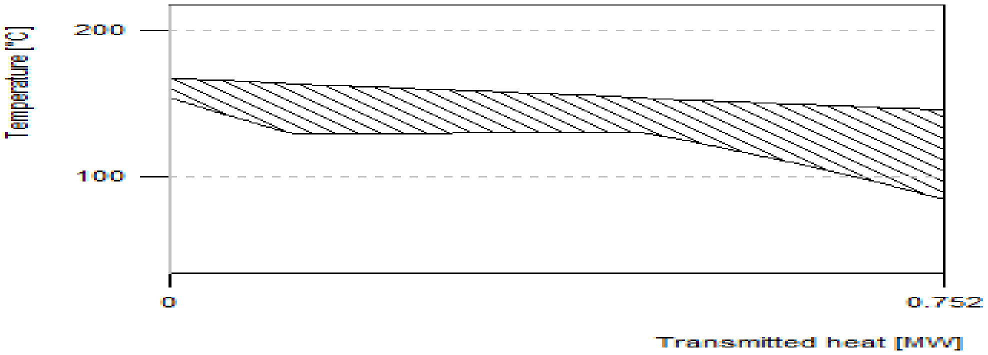


Fig. 4 - Q-T Diagram of the hot water and R-245fa temperature difference in the evaporator

The Fig. 4 shows the process of heat transfer in the received by the system. The heat input section is divided into two sections, which are the preheater taken from the diesel engine radiator and the evaporator from the diesel engine exhaust gas utilization. The function of the preheater is to increase the temperature of the working fluid before it enters the evaporator with the aim of changing the working fluid into a saturated liquid state. According to the equation above, exergy available on hot fluid is 433.04 kW, exergy losses from all component is 137.85 kW, and the exergy efficiency is 68.17%.

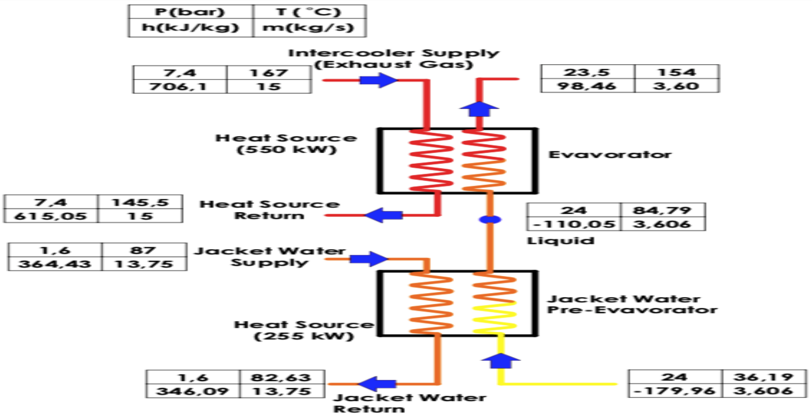


Fig. 5 - Thermal balance of heat input

The value of the total heat transfer coefficient (UA) for the ORC device design can be calculated from the simulation results above so that the heat exchanger device can be determined. The total heat transfer value in the evaporator from the calculation of UA and the logarithmic average temperature difference is obtained using.

4.4 Efficiency Comparison

The pump is one of the main components in the ORC system which functions to circulate the working fluid and to be able to achieve the desired working pressure. In addition, the pump is also a component that requires energy to work so that it will affect the net power output of the ORC system. In this simulation, five experiments were carried out using different pressures which of course would require different energies. The lower the desired pump output pressure, the less energy is required. The energy required is also very dependent on the mass flow rate of the fluid flowing in the system. In this case, the evaporation temperature does not influence the amount of energy required by the pump.

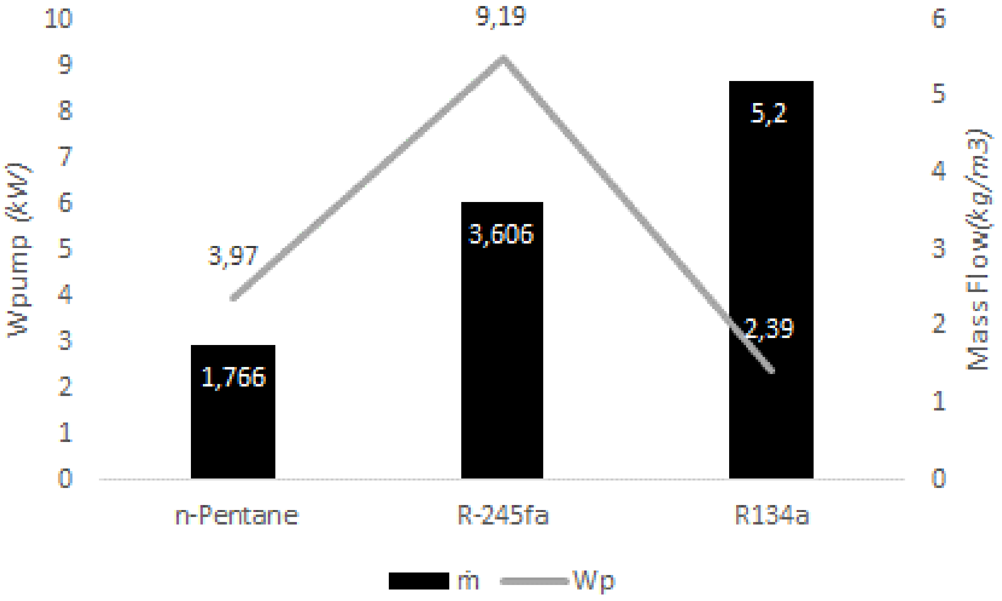


Fig. 6 - Relation of pump power and mass flow

The Fig. 6 shows the simulation results of a system that is conditioned at heat input (Qin) of ±1000 kW. The pump used for R-245fa will consume more energy of 9.19 kW which is greater than other working fluids. Compared to the pump used in the R-134a working fluid, it requires less energy even though the mass flow rate is higher. This is because the density of R-134a is much lighter than the other two working fluids.

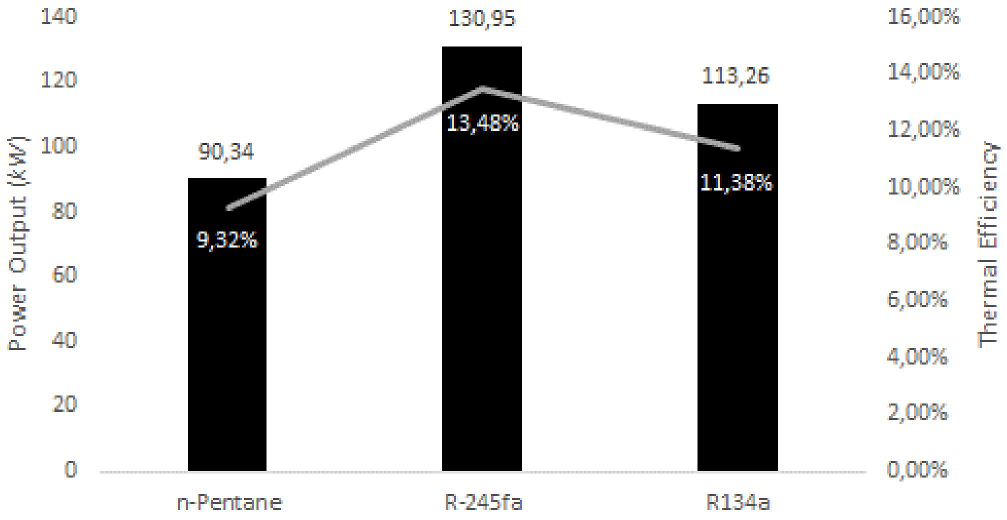
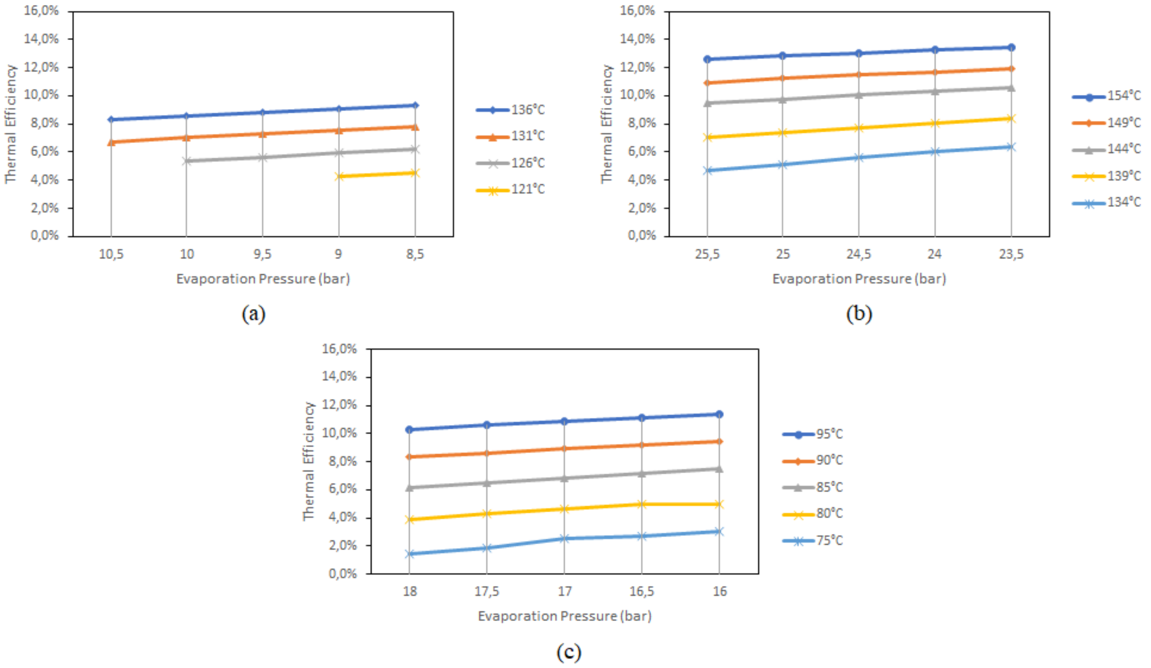


Fig. 7 - Net power at qin = 1000 kW

Assuming the generator efficiency is 97%, the net power output of the ORC system for each working fluid is shown in Fig. 7. The amount of electricity that can be generated from the simulation above is in the heat conditions received at the evaporator of 1000 kW. With higher thermal efficiency, R-245fa as working fluid can generate higher electricity.



(a)

(b)

(c)

Fig. 8 - Evaporation pressure and temperature affects system efficiency to each working fluid (a) n-Pentane; (b) R-245fa; (c) R-134a

Fig. 8 shows the effect of the evaporation pressure and temperature on the ORC system on the thermal efficiency of the system. The higher the evaporation temperature, the higher the thermal efficiency achieved, which means that more energy can be converted into electrical energy. This condition occurs in the three simulated working fluids. The energy transferred from circulating hot water to the ORC system will be more if the evaporator temperature is set higher. This is also influenced by the thermodynamic properties of the working fluid where the enthalpy value will be higher when given conditions of high temperature and lower pressure.

High thermal efficiency can be achieved by increasing the evaporation temperature. But, higher evaporation temperature requires higher pressure, so the working fluid condition stays in dry vapor state. Each fluid has different dry vapor pressure where the working pressure for R245fa higher than n-pentane and R134a. In spite of that, higher pressure requires higher pump energy. Density also greatly affect the work of the pump, R245fa and n-pentane has heavier density than R134fa causes larger pump workload. However, the higher the pressure and workload, the higher the cost of the equipment.

Table 3 - Resume of highest efficiency from each working fluid

Working Fluid	Evaporation Pressure (bar)	Evaporation Temperature (^{0}C)	Efficiency (%)
n-Pentane	16	136	11
R-245fa	23.5	154	13.48
R-134a	8.5	96	9.32

Table 3 shows that the highest thermal efficiency of 13.48% is obtained by using the working fluid R-245fa at the evaporator pressure and temperature of 23.5 bar and 154 ^{0}C, respectively. Followed by the working fluid R-134a which, when given the pressure and temperature conditions evaporation temperature of 16 bar and 96 ^{0}C will achieve a thermal efficiency of 11.38%. And the highest efficiency that can be achieved by the n-Pentane working fluid is 9.32% if the conditions in the evaporation process are at a pressure and temperature of 8.5 bar and 136^{0} C, respectively.

Exergy is energy that can be used (energy availability) or a proportion of energy accessibility to produce work. Exergy can be moved among system and can be lost because of irreversibility in the system. One of the primaries uses of the exergy idea is exergy stability with inside the analysis of thermal system. The identification and capability of these losses takes into account the assessment and improvement of the thermal design. The exergy evaluation method can display the quality and amount of heat loss and the place of energy degradation, so it can quantify and distinguish the reason for energy degradation.

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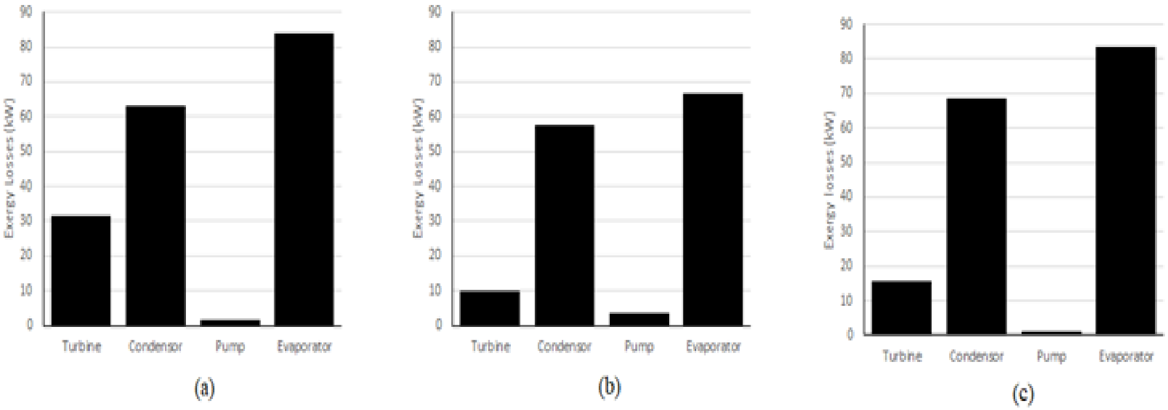

Fig. 9 - Exergy losses in each component for (a) n-pentane; (b) r-245fa; (c) r-134a

In this study, exergy analysis was also carried out for the ORC system to determine the irreversible loss of each component. As shown in Fig. 9, the exergy destruction rate of the evaporator and condenser in each working fluid is much higher due to the significant temperature difference in these two components. As for much lower turbines as well as for pumps, irreversible losses are very low.

5. Conclusion

In this paper, an evaluation of three working fluid on an Organic Rankine Cycle of a Waste Heat Recovery a technique has been proposed. The exhaust heat released by the diesel engine is utilized by adding an ORC system so that it can obtain additional energy without adding fuel. Evaluating using REFPROP and Cycle Tempo software was done by selecting the working fluid and setting the evaporation pressure and temperature to produce the highest system efficiency. The results from this study shown that the diesel engine with a capacity of 1000 kVa wastes 1177 kW of energy which is released through the exhaust pipe and engine radiator can produce a turbine power of 144.47 kW. The highest thermal efficiency of 13.48% was obtained by using the working fluid R-245fa at the evaporator pressure and temperature of 23.5 bar and 154^o C, respectively.

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