Performance Analysis of Working Fluids on Organic Ranking Cycle Using Waste Heat from Flue Gas

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Abstract

The increasing in electricity demand was inversely proportional to the supply of fossil fuels. It required various parties to find innovations to produce more electrical energy without increasing the use of fossil fuels. Organic Rankine Cycle (ORC) was one of the ways to generate electricity with a low heat source and it was affected by the type of refrigerant used as a working fluid. Therefore, this research was conducted to find a working fluid that produced good thermal efficiency and power for the ORC system by utilizing the flue gas from the steam power plant. Simulations were carried out using CoolProp software to determine the properties of the working fluid to be used and Cycle Tempo software to simulate the ORC system. This study used variations of working fluid R134a, R404A, R407C, R410A, and R507. In addition, flowrate variations of 100 kg/s, 150 kg/s, 200 kg/s, 250 kg/s, and 300 kg/s were also used. From this research, the highest thermal efficiency occurred at a flowrate of 300 kg/s using a working fluid R407C, it was 36.19%. The largest net power was also obtained at a flow rate of 300 kg/s using the working fluid R407C, it was 26980.9 kW.

Keywords: coolprop; cycle tempo; organic rankine cycle (orc); refrigerant; thermal efficiency

Abstrak

Meningkatnya kebutuhan listrik yang berbanding terbalik dengan ketersediaan bahan bakar fosil, menuntut berbagai pihak menemukan inovasi untuk menghasilkan energi listrik lebih banyak tanpa harus menambah penggunaan bahan bakar fosil. Siklus Organic Rankine Cycle (ORC) menjadi salah satu cara untuk dapat membangkitkan listrik dengan sumber panas bertemperatur rendah dan hal itu juga dipengaruhi oleh jenis refrigerant yang digunakan sebagai fluida kerja. Maka dari itu, dalam penelitian ini dilakukan untuk mencari fluida kerja yang menghasilkan efisiensi termal dan daya yang baik bagi sistem ORC dengan memanfaatkan panas buang dari flue gas PLTU. Simulasi dilakukan dengan software Cycle Tempo untuk simulasi sistem ORC dan software CoolProp untuk mengetahui properti dari fluida kerja yang akan digunakan. Penelitian ini menggunakan variasi fluida kerja R134a, R404A, R407C, R410A, dan R507. Selain itu, digunakan pula variasi flow rate sebesar 100 kg/s, 150 kg/s, 200 kg/s, 250 kg/s, dan 300 kg/s. Dari penelitian ini, dihasilkan efisiensi termal terbesar terjadi pada flow rate 300 kg/s dengan menggunakan fluida kerja R407C yaitu 36.19%. Net power terbesar juga didapatkan pada flow rate 300 kg/s dengan menggunakan fluida kerja R407C yakni 26980.9 kW.

Kata kunci: coolprop; cycle tempo; organic rankine cycle (orc); refrigerant; thermal efficiency

1. Introduction

The need for electricity is currently a primary need for humans. Many types of power plants have been developed, but the Steam Power Plant (PLTU) is still one of Indonesia's most reliable types of power plants. Electricity capacity in Indonesia reached 72750,73 MW in 2020 [1]. It takes various sources of energy other than PLTU and it is environmentally friendly to supply the electricity needs in Indonesia. One of the efforts to generate additional power is the utilization of exhaust gas from combustion in the PLTU boiler. It will improve the steam power plant energy efficiency and reduce the pollution of coal burning.

Exhaust gas or often called exhaust flue gas from boilers at PLTU normally has a relatively high temperature, which is between 120ºC to 150ºC. It still can be used as an additional heat to energy system. Exhaust flue gas also adds to the heat loss that occurs in the boiler, which is 50%-80% of the total heat loss in the boiler and 3-8% of the total energy input in the PLTU [2]. It suggests that recovering waste heat from exhaust flue gas boiler could increase the system's efficiency and reduce polluting emissions.

The use of exhaust flue gas boiler for waste heat has significantly improved in recent years. One of the methods that can be used to utilize waste heat is Organic Rankine Cycle (ORC). Organic Rankine Cycles (ORC) have been identified as the most promising heat engines to generate electricity from low-temperature heat sources. These low-temperature energy sources are typically available at temperatures of 80ºC to 150ºC [3]. Liu et al. [4] utilized the high-grade sensible heat of a natural gas boiler present in the flue gas using the ORC. Up to now, a considerable number of reported references focused on the basic theoretical researches about waste heat recovery using the ORC system, for example, the selection of working fluids [5]. The current studies demonstrate that the organic Rankine cycle (ORC) system is an effective method for recovering waste heat, which can convert low-grade waste heat into high-grade and clean electricity using low-boiling organic compounds as working fluids [6]. Therefore, ORC can be used to generate electricity by utilizing waste heat from the PLTU.

The organic fluids used by ORC systems are usually, Hydrofluorocarbon (HFC) refrigerants, ammonia (NH3), butane (C4H10), isopentane (C5H12), and toluene. Depending on the nature of the fluid, isentropic expansion from the dew curve may conserve, decrease, or increase the vapor titer [7]. In relation to the same subject, Yu et al. [8] studied the working fluids for Organic Rankine Cycles, their study shows that the most energy-efficient working fluids are R125, R143a, R290 and R1270 for ORCs. Wang et al. [9] researched eight working fluids, R113, R123, R245ca, R245fa, R600, R600a, R601, and R601a, with two heat sources in reaction-separation process of cumene synthesis. The several references regarding the working fluids, it can be concluded that variations in the working fluids are indeed very influential on the utilization of waste heat from exhaust flue gas boiler.

The desired working fluid should meet the requirements on environmental effects, thermophysical properties, chemical stability, etc. There are some desirable characteristics of working fluid in ORC: (1) The working fluids should have no Ozone Depletion Potential (ODP) and low Global Warming Potential (GWP), (2) to avoid the formation of the liquid droplet at the outlet of a turbine, dry or isentropic working fluids are more favorable, (3) the working fluids should have high chemical stability, (4) non-fouling, non-corrosiveness, non-toxicity and non-flammability, and (5) easy availability and low cost [8]. The qualities of the chosen refrigerant have a significant impact on how the refrigeration equipment is designed. The standard refrigerant designations, properties, and safety classifications are based on ASHRAE Standard 34 [10].

In this study, we will discuss the type of working fluid that produces the best thermal efficiency and power for the ORC cycle, by utilizing the heat contained in the exhaust gas. The research was conducted by simulation using CoolProp software to determine the properties of the working fluid to be used [3], those are R134a, R404A, R407C, R410A, and R507. Cycle Tempo software is also used to simulate the ORC system. From the simulation results in this study, it is expected that the type of refrigerant working fluid can optimize the performance of the ORC system.

2. Methods

2.1 Flue Gas

Flue gas is gas that comes from combustion components containing reaction products from fuel and combustion air as well as residual substances such as particulate matter (dust), sulfur oxide (SOx), nitrogen oxide (NOx), and carbon monoxide (CO) [11].

In addition to producing residue, exhaust flue gas is the biggest cause of heat loss in PLTU boilers, which ranges from 50%-80% of the total heat loss in the boiler (2). With temperatures between 120-150ºC, flue gas has potential heat that can be utilized rather than directly released into the atmosphere.

The equation that can be used to calculate the flue gas heat potential is in equation (1) [12]:

$$Q_{fg} = \dot{m}.C_p.\Delta T \quad (1)$$

Where Q_{fg} is flue gas heat in kW, $\dot{m}$ is mass flow rate in kg/s, C_p is specific heat of flue gas kJ/kg.K , and ΔT is exhaust gas temperature difference in K.

2.2 Organic Rankine Cycle

Organic Rankine Cycle (ORC) is a cycle system that is similar to the conventional Rankine cycle, only the difference is the working fluid used. The Rankine cycle uses water as the working fluid while the ORC uses an organic fluid (refrigerant) as the working fluid. The use of this organic fluid allows the working fluid to evaporate even though the heat source used by the generator has a low temperature. In addition to the working fluid, the difference between the Rankine and ORC cycles is in the heating component. The Rankine cycle uses a boiler to heat the working fluid while the ORC uses an evaporator as a heater. The cycle scheme along with the T-s diagram of the ORC cycle can be seen in Figure 1. The components used in the Organic Rankine Cycle (ORC) include:

The pump is a component for moving liquids from one place to another with a pipe medium. The equation for mass and energy balance in the pump [12], is shown by equation (2).

$$\frac{W_p}{\dot{m}_f} = (h_2 - h_1) \quad (2)$$

Where $\dot{W}_p$ is pump power in kW, $\dot{m}_f$ is mass flow rate of working fluid in kg/s, h_2 is enthalpy of working fluid at exit of pump in kJ/kg, h_1 is enthalpy of working fluid at pump suction in kJ/kg.

$$\dot{W}_p = \dot{m}_f \frac{(p_2 - p_1)}{\eta_p} \quad (3)$$

Where p_2 is discharge pressure in bar, p_1 is suction pressure in bar, and η_p is efficiency of isentropic turbine in %.

The evaporator acts as a heating component in the ORC. The balance of mass and energy in the evaporator [12] is expressed by equation (4).

$$\frac{Q_{Evap}}{\dot{m}_f} = (h_3 - h_2) \quad (4)$$

Where Q_{Evap} is heat entering the system in kJ and h_3 is enthalpy of working fluid at evaporator inlet in kJ/kg.

Steam turbine is a device used to convert energy from superheated steam into motion energy. The balance of mass and energy in a steam turbine [12] is shown by equation (5).

$$\frac{\dot{W}_t}{\dot{m}_f} = (h_4 - h_3) \quad (5)$$

Where $\dot{W}_t$ is power generated by the turbine in kW and h_4 is enthalpy of working fluid at exit of turbine in kJ/kg .

The condenser is used to change the phase of the steam coming from the turbine. The mass and energy balance in the condenser [12] is expressed in equation (6).

$$\frac{Q_{con}}{\dot{m}_f} = (h_4 - h_1) \quad (6)$$

Where Q_{con} is heat removed in kW.

The calculation of thermal efficiency can be formulated in equation (7) [12].

$$\eta = \frac{\dot{W}_{net}}{Q_{Evap}} = \frac{\dot{W}_t - \dot{W}_p}{Q_{Evap}} \quad (7)$$

Where η is thermal efficiency in % and $\dot{W}_{net}$ is overall generated power in kW.

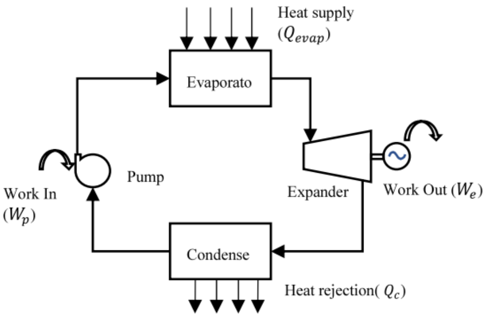

Figure 1. Organic Rankine Cycle

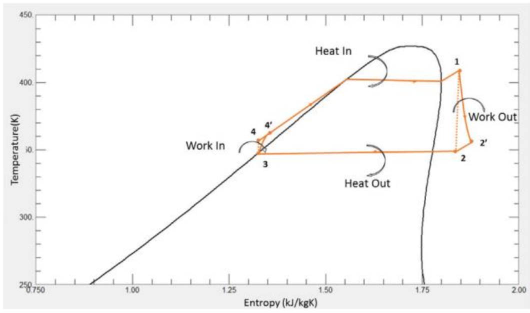

Figure 2. T-s diagram of ideal ORC

2.3 Refrigerant

Refrigerant is a fluid that works in refrigeration systems, air-conditioning, and heat pump systems [10]. Refrigerants work by absorbing heat from one area and releasing that heat in another, usually through the process of evaporation and condensation.

The choice of working fluid will refer to several factors. In terms of safety, the choice of working fluid refers to ASHRAE Standard 34. According to this standard, the working fluid must be in group A1 because refrigerants included in this group are non-toxic and non-flammable. Based on the impact of the refrigerant on the environment, a working fluid that has a low ODP and GWP value is needed so that the working fluid has a low potential to affect ozone and global warming.

Furthermore, the selected working fluid must have a low boiling point so that the working fluid can evaporate even with a low heat source. From the performance factor, a working fluid that has high thermal conductivity was chosen so that the refrigerant used can conduct heat better. In addition, the selected refrigerant has a low viscosity value to minimize surface tension between the working fluid and the ORC cycle components. Because fluids with low viscosity flow more easily so that the pump can work more optimally. Therefore, several working fluids were selected which were simulated in this study as shown in Table 1.

3. Result and Discussion

3.1 Flue Gas Heat Potential Analysis

The flue gas heat potential is calculated based on the data used by Syed et al. in their research entitled "Waste Heat and Water Recovery System Optimization for Flue Gas in Thermal Power Plants" [13]. by using equation (1).

$$Q_{fg} = 750\,\frac{kg}{s}(1.131)\frac{kJ}{kg.K}(4423 - 331.63)K$$

$$Q_{fg} = 77530.05kW$$

It was found that the heat potential of flue gas from the previous data was 77.53 MW. When compared with research conducted by [14], wherein the journal the heat potential obtained is 6034 kW. The heat potential of flue gas is much higher, so it has the potential to utilize exhaust heat by using the ORC cycle.

3.2 Organic Rankine Cycle Simulation

The arrangement of the ORC system simulation was carried out based on the data obtained from the data in the research of Syed et al. and simulated using Cycle Tempo software. Figure 3. is the arrangement of the ORC cycles in Cycle Tempo. The type of physical model solver used in this study can be seen in the Table 1. After all the components to be simulated have been arranged as shown in Figure 3, using the simulation parameters as in Table 2.

Table 1. Properties of refrigerants

Parameter	R-134a	R-404A	R-407C	R410A	R507
Type	HFC	HFC Mixed	HFC Mixed	HFC Mixed	HFC Mixed
Chemical Formula	CH_2FCF_3	R-125, R-143a, R-134a (44/52/4 %Mass)	R-32, R-125, R-134a (23/25/52 %Mass)	R-125, R-32 (50/50 %Mass)	R-125, R-143a (50/50 %Mass)
Safety Group	A1	A1	A1	A1	A1
Molecular Weight	102	97.6	86.2	72.6	98.9
Boiling Point (ºC)	-26	-46.56	-42	-51.58	-46.7
Critical Temperature (ºC)	101.06	72.046	86.034	72.13	70.9
Critical Pressure (Mpa)	4.059	3.729	4.63	4.926	3.79
Spcific Volume (m^3/kg)	0.00083	0.00095	0.00088	0.00094	0.00095
ODP	0	0	0	0	0
GWP	1790	3900	1800	2100	3985
Parameter	R-134a	R-404A	R-407C	R410A	R507

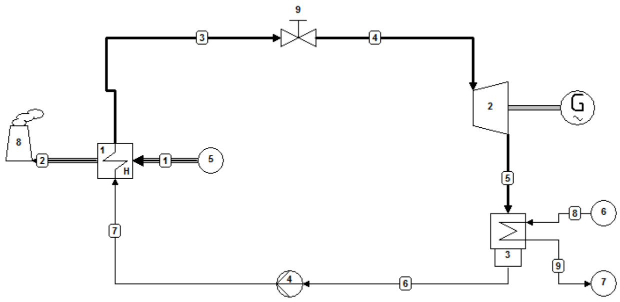

Figure 3. Arrangement of ORC components at Cycle Tempo

Table 2. ORC simulation parameters

Parameter	Unit	Value
Flue gas inlet temperature	ºC	150
Flue gas outlet temperature	ºC	58.6
Pressure of flue gas	kPa	100
Flow rate of flue gas	kg/s	750
Heat potential from flue gas	MW	77.53

3.3 Data Validation

Validation is a process carried out to ensure that the simulation data is valid. Data validation can show that the model that has been made for the simulation is in accordance with the reference data [14]. Based on Table 3, it is shown that the data from the simulation results of the ORC system in Cycle Tempo with data from the reference has a relatively small error value, which is below 5%. This indicates that the simulation carried out is in accordance with the journal and the simulation can be continued to the next stage, namely adding variations.

Table 3. Validation table

Parameter	Journal Data	Simulation Data	Error
T *in* Evap (ºC)	31.098	32.14	3.351%
T *out* Turbin (ºC)	33.634	33.64	0.018%
T *in Cond*. (ºC)	33.634	33.63	0.012%
T*out Cond* (ºC)	33.634	33.64	0.018%
T*out* Pump (ºC)	31.09	32.14	3.377%
P Turbine (kW)	7624.98	7623.45	0.020%
P Generator (kW)	7624.98	7547.21	1.020%
h *in* Evap (kJ/kg.K)	243.3	244.79	0.612%
h *out* Evap (kJ/kg.K)	437.81	437.82	0.002%
h *in* Turbine (kJ/kg.K)	437.81	437.82	0.002%
h *out* Turbine (kJ/kg.K)	418.63	418.65	0.005%
h *out* Pump (kJ/kg.K)	243.3	244.79	0.612%

3.4 Analysis Data

Refrigerant Analysis

A substance that is in the liquid phase but has not 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 a mixture of liquid and gas, the mass fraction of a fluid or substance is called the quality or the ratio of the saturation mass of the gas and the mass of the saturated liquid with a value between 0 (liquid saturation) to 1 (gas saturation) [15]. The properties of the refrigerant used as a working fluid were obtained using the CoolProp software. The following is a table of data collection properties of the refrigerant working fluid:

Table 4. The result of working fluid analysis

Working Fluids		**T (ºC)**	**P (bar)**	**Enthalpy (kJ/kg.K)**	**Quality (kg/kg)**
R134a	Turbine Inlet	95	9	479.18	Superheated
	Condenser Outlet	30	7	236.99	Subcooled
R404A	Turbine Inlet	95	15	449.06	Superheated
	Condenser Outlet	30	13	236.88	Subcooled
R407C	Turbine Inlet	95	14	488.89	Superheated
	Condenser Outlet	30	12	238.04	Subcooled
R410A	Turbine Inlet	95	20	502.88	Superheated
	Condenser Outlet	30	18	246.4	Subcooled
R507A	Turbine Inlet	95	16	444.22	Superheated
	Condenser Outlet	30	14	239.67	Subcooled

The analysis performed with CoolProp software produces temperature, pressure, and working fluid phase data that will be simulated. The working fluids property data are shown in Tables 4, there are working fluid conditions that will be simulated using Cycle Tempo software along with the quality of the fluid. The working fluid property data is taken when the fluid enters the turbine and exits the condenser.

It can be seen that each working fluid has varying properties. In Table 4, the working fluid R134a has entered the superheated phase at a pressure of 9 bar and is in the subcooled phase at a pressure of 7 bar. Furthermore, for the working fluid R404A enters the subcooled phase at a pressure of 13 bar and is at a pressure of 15 bar to reach the superheated phase. The working fluid R407C has reached the superheated phase at a pressure of 14 bar and has reached the subcooled phase at a pressure of 12 bar. The working fluid R410A requires the highest pressure to enter the superheated phase among the other five working fluids, which is 20 bar, and to enter the subcooled phase R410A requires a pressure of 18 bar. Finally, the working fluid R507 is in the superheated phase at a pressure of 16 bar with a pressure of 14 bar to enter the subcooled phase.

Analysis of Organic Rankine Cycle Performance

The heat transfer rate on the ORC evaporator can be seen in Figure 4. It can be seen that with each increase in the value of the working fluid flow rate, the rate of heat transfer that occurs also increases. If the evaporator gets constant heat, then the evaporator Q should be constant. As the refrigerant flow rate increases, the fluid is already out before it can absorb heat from the evaporator. This phenomenon can be explained by equation 4. Moreover, the flow rate variation used has a significant value. The resulting data shows that R410A has the best heat transfer rate followed by R407C and R134a. While the working fluid R404A and R507 have the worst heat transfer rate. This difference in value can be caused by the value of the thermal conductivity of each working fluid. R410A has the best thermal conductivity so that this refrigerant can absorb heat from the evaporator better than other refrigerants. R410A has the best thermal conductivity so that this refrigerant can absorb heat from the evaporator better than other refrigerants.

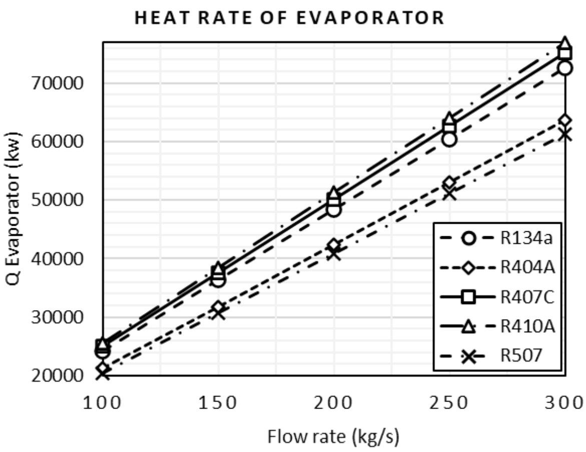

Figure 5. Heat rate of evaporator

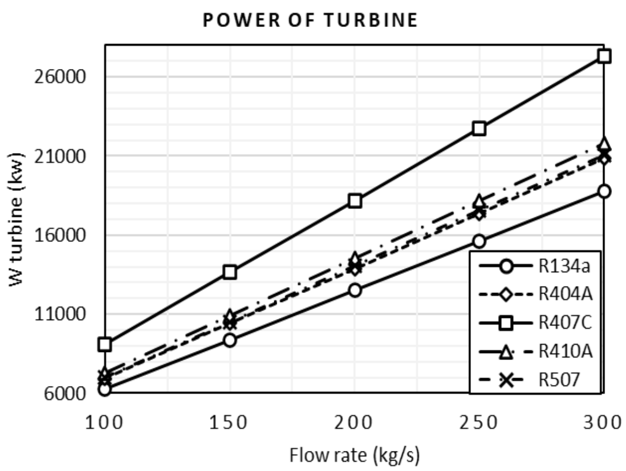

Figure 4. Power of turbine

The work of the ORC turbine is shown in Figure 5. It can be seen that the value of the turbine power increases as the flow rate increases. This increase in turbine power is caused by an increasing flow rate resulting in greater turbine blade momentum, resulting in greater turbine rotation.

In Figure 5. it can be seen that the working fluid R407C produces the greatest power, which is 9099.09 kW at a flow rate variation of 100 kg/s and the highest is 27297.26 kW at a flow rate variation of 300 kg/s. This can be caused by the decrease in enthalpy at R407C which is greater than other working fluids.

The heat transfer rate that occurs in the condenser is shown in Figure 6. The highest heat transfer rate in the condenser is owned by R410A and R134a have values that are not much different, followed by R407C, R404A, and R507 last. The result is the same as the heat rate in the evaporator. This can be explained by equation 6. However, in general, the enthalpy will decrease the flow rate used is greater than the outflow will go through the condenser first before the heat is absorbed by the condenser cooler so that the heat in the condenser is still high. It is also caused by the different thermal conductivity of the working fluid. The working fluid R410A has the best thermal conductivity, then R407C, R134a, R404A, and the one with the lowest thermal conductivity is R507.

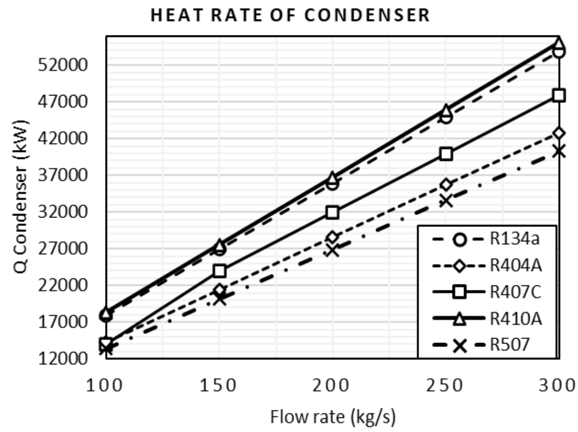

Figure 7. Heat rate of condenser

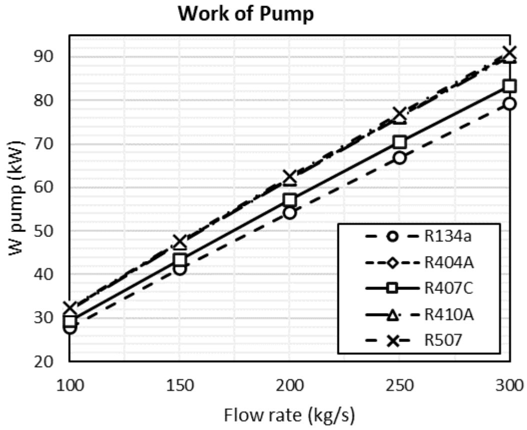

Figure 6. Work of pump

The pump work on the ORC system is shown in Figure 7. It can be seen that the pump work is getting bigger as the flow rate of the working fluid increases. This happens because the large working fluid flow rate causes more working fluid on the suction side so that the pump has to work extra to pump the fluid.

The pump work in this ORC simulation is in accordance with equation 3 where the pump performance is influenced by the specific volume of the working fluid. Specific volume is the ratio of the volume of the material to its mass. The volume of this type is inversely proportional to the density and also inversely proportional to the density value. The graph also shows that the working fluids R404A, R410A, and R507 have pump work that has very little difference from each other. When the refrigerant also has a higher pump work compared to R134a and R407C.

Thermal efficiency is the quotient between the energy obtained and the energy required. A Rankine cycle is said to be efficient when the turbine is able to produce a large amount of energy from the consumption of heat energy from the boiler and the energy of the pump motion is minimal [12]. In this ORC simulation, the results of the thermal efficiency are shown in Figure 8.

The thermal efficiency graph shows that the working fluid R407C has the best thermal efficiency. Then R507 is the working fluid with the second-best efficiency and R404A has a value below R507 which is not far apart. For R410A and R134a are working fluids with the lowest thermal efficiency values with a slight difference.

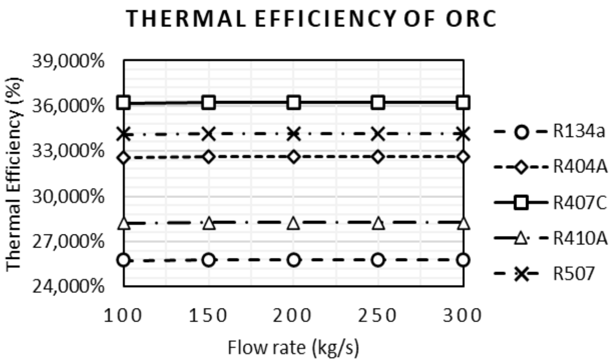

Figure 9. Thermal efficiency of ORC

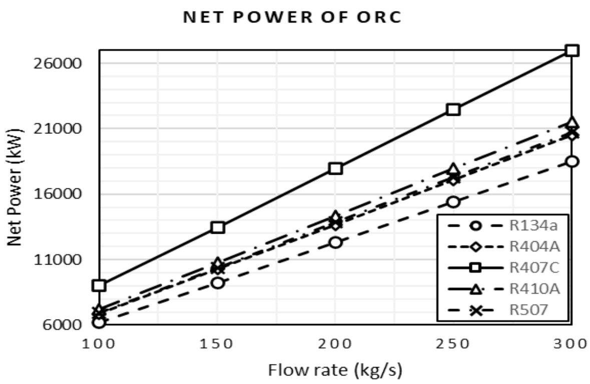

Figure 8. Net power of ORC

Although the work of the R407C evaporator is the second highest of all working fluids, the turbine work of R407C has the best results and the work of the R407C pump is the smallest. Therefore, the resulting thermal efficiency is quite high, which is around the value of 36.19%. The working fluid R507 has the second high thermal efficiency with a value of about 34.1% and furthermore R404A has a fairly good thermal efficiency of 32.5%. R507 and R404A consume relatively little energy from the evaporator but they are not capable of producing large turbine power and both pump power consumption is quite high. Furthermore, R410A and R134a have a thermal efficiency of 28.2% for R410A and 26.8% for R134a. R410A produces higher turbine power than R507 and R404A, only R410A consumes energy from the evaporator the most so it has less thermal efficiency.

In addition to producing thermal efficiency, Figure 9, net power data is also obtained in each variation of refrigerant and flow rate. The net power value is obtained from the power generated by the generator minus the power consumed by the pump. The highest net power is generated by the R407C. Next there is R410A and the working fluid R507 and R404A with a difference that is not far apart. The last one is R134a.

The Figure 8 shows that the flow rate has an effect on increasing the value of thermal efficiency but the effect is not significant. Flow rate also affects the resulting net power. With the increase in the flow rate of the working fluid causing more fluid to pass through the ORC components so that more heat is transferred and the performance of each ORC component also increases so that the thermal efficiency and net power will also be higher.

4. Conclusion

Based on the research results that have been obtained, it can be concluded that the performance of heat exchanger components such as evaporator and condenser is affected by the thermal conductivity of the working fluid used. The working fluid with the best heat transfer rate is R410A. The working fluid that has the best pump work and the smallest viscosity is R507. The working fluid that produces the highest turbine power is R407C with the power of each flow rate variation of 9099.09 kW; 13648.63 kW; 18198.17 kW; 22747.72 kW; 27297.26 kW.

Variations in flow rate can affect the work of each ORC component. The greater the flow rate given, the greater the component work, and the net power will be. However, flow rate does not have a significant effect on thermal efficiency. The greatest thermal efficiency occurs at a flow rate of 300 kg/s using a working fluid R407C, which is 36.19%. The largest net power is also obtained at a flow rate of 300 kg/s using the working fluid R407C, which is 26980.9 kW.

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