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Open feed organic heater pressure analysis on single-stage regenerative organic Rankine cycle performance

Ghalya Pikra [a,*], Nur Rohmah [b], Rakhmad Indra Pramana [a], Andri Joko Purwanto [a]

[a] *Research Centre for Electrical Power and Mechatronics, Indonesian Institute of Sciences*
Komp LIPI Bandung, Gd 20, Lt 2, Bandung, West Java, 40135 Indonesia
[b] *Research Unit for Clean Technology, Indonesian Institute of Sciences*
Komplek LIPI Bandung, Gedung 50, Bandung, West Java, 40135, Indonesia

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Abstract

Single-stage regenerative organic Rankine cycle (SSRORC) is a system that is used for increasing the simple organic Rankine cycle (ORC) performance. Open feed organic heater (OFOH) addition in the ORC system increase power and efficiency of the system. This paper analyzes the SSRORC performance with a variation of P_6/P_1 ranges from 1.25 to 3.75 with an increment of 0.25, where P_6 is the OFOH pressure at the inlet side and P_1 is the pressure at the inlet pump 1, respectively. Hot water was used as the heat source with 100 °C and 100 l/min of temperature and volume flow rate as the initial data. R227ea, R245fa, and R141b were chosen as working fluids for performance analysis. The analysis was performed by calculating the heat input, heat loss, pump and turbine power, net power, and thermal efficiency through energy balance. Exergy input, exergy output, and exergy efficiency were analyzed through exergy balance. The results show that $P_6/P_1 = 2$ obtains the highest performance than the other pressure ratios for R227ea, while R245fa and R141b obtain the highest performance at $P_6/P_1 = 2.25$. R141b has better performance than the other two fluids with 10.97 % and 11.96 % for thermal and exergy efficiency. The results show that the ratio of OFOH pressure at the inlet side to the pressure at inlet pump 1 (P_6/P_1) in the middle value obtains the best performance.

Keywords: single-stage regenerative organic Rankine cycle; open feed organic heater; R227ea; R245fa; R141b.

I. Introduction

Electricity needs are increasing in this globalization era. On the other hand, the availability of fossil fuels is running low, so it is necessary to find other alternative sources before fossil fuels could no longer meet the world's electricity demands. Renewable energy has begun to be developed in various parts of the world. During this time, the Rankine cycle has been known as one of the many power generation systems developed and used to generate electricity. Water is commonly used as a working fluid that can only generate electricity at high operating temperatures, whereas existing renewable energy such as geothermal, solar, and waste heat allows it to be used as a heat source to generate electricity at low and medium operating temperatures so that the use of water must be replaced for the renewable energy utilization. Therefore, organic fluids which have lower boiling temperatures than water can be used in the system to produce electricity at low and medium operating temperatures. This system is known as the organic Rankine cycle (ORC) which has the same components as the Rankine cycle but can produce electricity at low and moderate operating temperatures by using organic fluid as a working fluid.

Organic Rankine cycle (ORC) has been utilized in many heat sources, such as biomass [1], geothermal [2][3][4], solar [5], ocean thermal [6], and waste heat [7][8][9]. This system can also be combined with other cycles so that the use of heat sources can be maximized and the heat loss in the system can be reduced. However, because of the low operating temperature, the ORC system has a low performance.

Modification of the ORC configuration is one of many ways that can be used to increase the ORC

* Corresponding Author. Phone: +6222-2503055
E-mail address: ghalya30@gmail.com; ghal001@lipi.go.id

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system performance. Many ORC configurations have been studied and experimented by many researchers in order to enhance the system performance. Li *et al.* compared parallel and series of two-stage organic Rankine cycle and as a result, the series configuration has a better performance than the parallel [10]. K. Braimakis and S. Karellas investigated an open and closed preheater that resulting in better performance by using a closed preheater [11]. Li *et al.* optimized the ORC using dual-pressure evaporation and analyze nine different working fluids with 100-200 °C of heat source temperature.

The optimization showed an increase in net power output between 21.4 – 26.7 % [12]. Sciubba *et al.* compared double stage ORCs and a recuperator addition that resulting in an electricity generation increment up to 8.11 % and 2.67 %, respectively [8]. Mosaffa *et al.* studied regenerative and recuperative ORCs for geothermal energy that obtain high efficiency [4]. Xi *et al.* optimized the ORC using single and double stage regenerative ORCs and shows that the double stage has the highest energy and exergy efficiency [13]. Zare compared three configurations such as a simple ORC, a recuperative ORC, and an open-type regenerative preheater ORC for binary geothermal power plants. The result shows that simple ORC obtains the highest power output and the lowest economic cost, and recuperative ORC observed the best energy and exergy efficiency [14]. Safarian and Aramoun evaluated a simple and regenerative-recuperative ORC and examined that the regenerative-recuperative ORC has the best thermal efficiency [15].

Single-stage regenerative organic Rankine cycle (SSRORC) is one of many configurations that can increase the ORC system performance. Inspired from our previous research [16] about the performance comparison of single SSRORC and double stage of regenerative organic Rankine cycle (DSRORC), this paper discusses the pressure analysis of an open feed organic heater (OFOH) in a single-stage regenerative organic Rankine cycle (SSRORC), since our previous research assumes that the pressure entering the OFOH is constant. Eleven different pressure values are investigated to determine the best performance. Those pressures were based on the ratio of pressure at inlet pump 1 and the pressure at inlet OFOH, that is, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 2.75, 3, 3.25, 3.5, 3.75. Temperature and volume flow rate of 100 °C and 100 l/min are used as the initial data using water as the heat source. Three working fluids such as R227ea, R245fa, and R141b are compared and analyzed to determine the best performance. Because the pressure at inlet OFOH must be lower than the inlet turbine pressure, then R227ea can only be used until the maximum pressure ratio of 3.25.

II. Materials and Methods

A simple organic Rankine cycle consists of four main components, such as evaporator, turbine, condenser, and pump. A modification of the ORC system configuration is necessary to increase its performance. Open feed organic heater (OFOH) addition in the ORC system is one of many modifications that can enhance the system performance. The addition of OFOH in the system is commonly called as a single-stage regenerative organic Rankine cycle (SSRORC). Figure 1 shows the scheme of SSRORC.

The working principle of SSRORC that is shown in Figure 1 is almost the same with the simple ORC. The simple ORC only uses one pump and do not use an open feed organic heater (OFOH). In the simple ORC, the fluid from the condenser (1) is directly pumped to the evaporator (4) to be vaporized and expanded in the turbine (5). All of the expanded fluids are condensed in the condenser (7) to be pumped back to the evaporator (4). The SSRORC has an OFOH (6) and one additional pump (3) so that some of the expanded fluids from the turbine flow directly to the OFOH (6) while some other fluids are condensed in the condenser (7) prior to being pumped back to OFOH and finally be pumped to the evaporator. This configuration has a possibility to decrease the heat loss in the condenser and subsequently increase the system performance.

This paper analyzes the OFOH pressure influence on the performance of the SSRORC system. It analyzes eleven states of OFOH pressure from the ratio of pressure at inlet pump 1 (P_1) and the OFOH inlet (P_6). The P_6/P_1 values used in this study are 1.25,

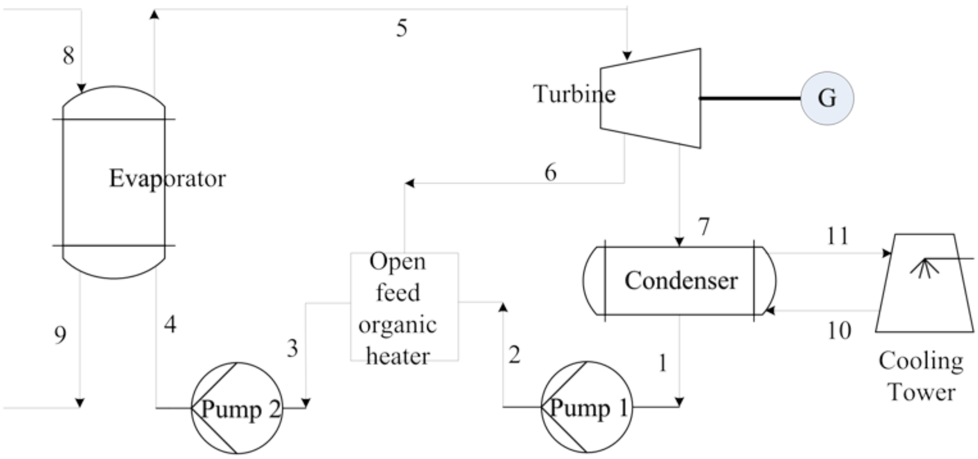

Figure 1. Configuration of single-stage regenerative organic Rankine cycle (SSRORC)

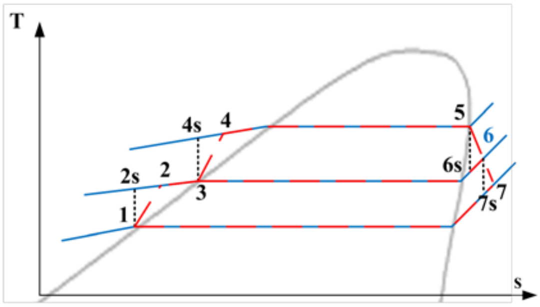

Figure 2. T-s Diagram of SSRORC

1.5, 1.75, 2, 2.25, 2.5, 2.75, 3, 3.25, 3.5, and 3.75. The T-s diagram from Figure 2 shows all states at each component of SSRORC.

Figure 2 shows that the pressure at the state 1 (P_1) is the same as the pressure at 7 (P_7), the pressure at 2 (P_2) is the same as the pressure at 3 and 6 (P_3 and P_6), and the pressure at 4 (P_4) is the same as the pressure at 5 (P_5). The pressure at 6 as shown in Figure 2 is made varied for the analysis requirement. The performance analysis was carried out using the first and second laws of thermodynamics through energy and exergy balance from Moran *et al.* [17]. Figure 3 shows the flowchart of the analysis.

Figure 3 shows that the initial temperature and volume flow rate of the heat source (water) for all fluids and all states are assumed to be constant at 100 °C and 100 l/min. The inlet temperature of the turbine (T_5) is 90 °C which is at saturated vapor state, and the inlet temperature of the pump 1 (T_1) is 40 °C which is at saturated liquid state. Both states are assumed constant for various P_6. Isentropic efficiency of the pump and the turbine are assumed 0.75 and 0.85, while the potential and kinetic energy are negligible.

The analysis started with heat input (Q_{in}) and heat loss (Q_{loss}) calculation from energy balance at the evaporator and condenser. The calculation was continued with pump power (W_p) and turbine power (W_t) calculation from energy balance at the pump and the turbine to determine the net power output. The thermal efficiency (η_{th}) obtained from the ratio of net power output and the heat input. The calculation of Q_{in}, Q_{loss}, W_p, W_t, and η_{th} is shown in Equations (1) to (5)

$$Q_{in} = \dot{m}_{of}(h_5 - h_4) = \dot{m}_{hw}Cp_{hw}(T_9 - T_8) \quad (1)$$

$$Q_{loss} = \dot{m}_{of}(1 - y)(h_7 - h_1) \quad (2)$$

$$W_p = \dot{m}_{of}[(h_4 - h_3) + (1 - y)(h_2 - h_1)] = \dot{m}_{of}/\eta_p\,[(h_{4s} - h_3) + (1 - y)(h_{2s} - h_1)] \quad (3)$$

$$W_t = \dot{m}_{of}[(h_5 - h_6) + (1 - y)(h_6 - h_7)] =$$

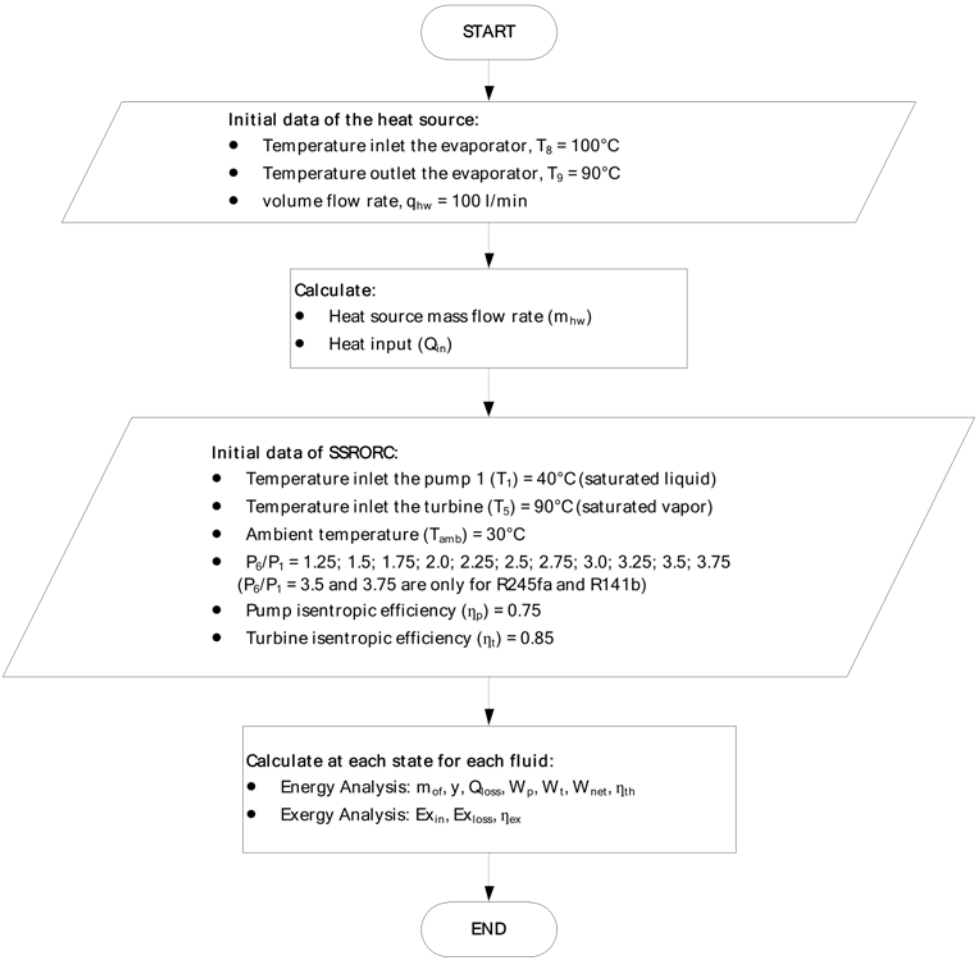

Figure 3. Flowchart of SSRORC performance analysis

$$\dot{m}_{of}\eta_t[(h_5 - h_{6s}) + (1 - y)(h_6 - h_{7s})] \quad (4)$$

$$\eta_{th} = \frac{W_t - W_p}{Q_{in}} = \frac{W_{net}}{Q_{in}} \quad (5)$$

where Q_{in} is heat input (kW); $\dot{m}_{of}$ is the organic fluid mass flow rate (kg/s); $\dot{m}_{hw}$ is heat source mass flow rate (kg/s); Cp_{hw} is heat source heat capacity (kJ/kg K); T_8 is heat source temperature at inlet evaporator (°C); T_9 is heat source temperature at outlet evaporator (°C); W_{net} is net output (kW); Q_{loss} is heat loss (kW); W_p is pump power (kW); W_t is turbine power (kW); h_1 is organic fluid enthalpy at inlet pump 1/outlet condenser (kJ/kg); h_2 is organic fluid enthalpy at inlet OFOH/outlet pump 1 (kJ/kg); h_{2s} is isentropic organic fluid enthalpy at inlet OFOH/outlet pump 1 (kJ/kg); h_3 is organic fluid enthalpy at outlet OFOH/inlet pump 2 (kJ/kg); h_4 is organic fluid enthalpy at outlet pump 2/inlet evaporator (kJ/kg); h_{4s} is isentropic organic fluid enthalpy at outlet pump 2/inlet evaporator (kJ/kg); h_5 is organic fluid enthalpy at outlet evaporator/inlet turbine (kJ/kg); h_6 is organic fluid enthalpy at outlet turbine/inlet OFOH (kJ/kg); h_{6s} is isentropic organic fluid enthalpy at outlet turbine/inlet OFOH (kJ/kg); h_7 is organic fluid enthalpy at outlet turbine/inlet condenser (kJ/kg); h_{7s} is isentropic organic fluid enthalpy at outlet turbine/inlet condenser (kJ/kg); η_p is isentropic efficiency of the pump; η_t is isentropic efficiency of the turbine; η_{th} is thermal efficiency (%); and y is the fraction of steam extracted.

Exergy input (Ex_{in}), exergy loss (Ex_{loss}), and exergy efficiency (η_{ex}) are the parameter that would be calculated from the exergy side. The calculation of Ex_{in}, Ex_{loss}, and η_{ex} are shown in Equations (6) to (8)

$$Ex_{in} = \dot{m}_{of}[h_5 - h_4 - T_{amb}(s_5 - s_4)] \quad (6)$$

$$Ex_{loss} = \dot{m}_{of}(1 - y)[h_7 - h_1 - T_{amb}(s_7 - s_1)] \quad (7)$$

$$\eta_{ex} = \frac{W_t - W_p}{Ex_{in}} = \frac{W_{net}}{Ex_{in}} \quad (8)$$

where Ex_{in} is exergy input (kW); Ex_{loss} is exergy loss (kW); η_{ex} is exergy efficiency (%); T_{amb} is ambient temperature (°C); s_1 is organic fluid entropy at inlet pump 1/outlet condenser (kJ/kg K); s_4 is organic fluid entropy at outlet pump 2/inlet evaporator (kJ/kg K); s_5 is organic fluid entropy at outlet evaporator/inlet turbine (kJ/kgK); and s_7 is organic fluid entropy at outlet turbine/inlet condenser (kJ/kg K).

R227ea, R245fa, and R141b are chosen as the working fluid for the analysis. They are chosen because they are suitable to be used at a low to medium heat source temperature [18][19]. The properties of the three fluids are shown in Table 1 [20][21].

Wet fluid type is not used in the analysis because it is more appropriate to be used for high temperature and the superheated condition [22][23]. A dry and isentropic fluid is a fluid type that is suitable to be used for a low and medium grade heat source [21].

III. Results and Discussions

The performance analysis is divided into 5 sections, that is heat input and heat loss analysis, pump and turbine power analysis, net power output and thermal efficiency analysis, exergy input and exergy output analysis, and lastly, the exergy efficiency analysis. The five sections are depicted as the step of the energy and exergy analysis to obtain the system performance of SSRORC with various OFOH pressure.

A. Heat input and heat loss analysis

The results of heat input (Q_{in}) and heat loss (Q_{loss}) calculations for three fluids in all eleven pressure values at the OFOH inlet the OFOH are shown in Figure 4. Figure 4 shows the same heat input values for all fluids at different P_6/P_1 because of the constant initial data for all states and all fluids. Equation (1) shows that Q_{in} is influenced by the mass flow rate ($\dot{m}_{hw}$), heat capacity (Cp_{hw}), and temperature differences ($T_9 - T_8$) of the heat source. Those three parameters are constant for all fluids and all P_6/P_1, hence the Q_{in} becomes constant.

Figure 4 shows the heat loss (Q_{loss}) for R227ea obtains the highest value and R141b obtains the lowest Q_{loss} among the three different fluids. This condition is connected to the properties of each fluid that is shown in Table 1, where R227ea has the lowest critical pressure and R141b has the highest critical pressure. The result determines that R227ea with the lowest critical pressure obtain a lower pressure at the same P_6/P_1 than the other fluids, thus made R227ea obtains the highest Q_{loss} than others. R227ea obtains the lowest Q_{loss} at P_6/P_1= 2, and the highest result is obtained from P_6/P_1 = 3.25. R245fa and R141b obtain their lowest Q_{loss} at P_6/P_1 = 2.25, and their highest result is obtained from P_6/P_1= 3.75. Figure 3 shows that the middle value between the ratio of OFOH pressure at the inlet side (P_6) and pump 1 (P_1) pressure at the inlet side shows the lowest heat loss for all fluids.

B. Pump power and turbine power analysis

Figure 5 shows the result of pump power and turbine power calculations for three fluids in eleven states of pressure at inlet the OFOH. Figure 5 shows the highest W_p obtained by R227ea, and the lowest

Table 1.
Properties of R227ea, R245fa, and R141b [20][21]

Properties	R227ea	R245fa	R141b
Molecular Weight (g/mol)	170.03	134.05	116.95
Boiling Temperature (°C)	-16.19	15.29	32.2
Critical Temperature (°C)	101.9	154.16	204.5
Critical Pressure (bar)	28.7	36.1	42.1
Type	Dry	Dry/Isentropic	Isentropic

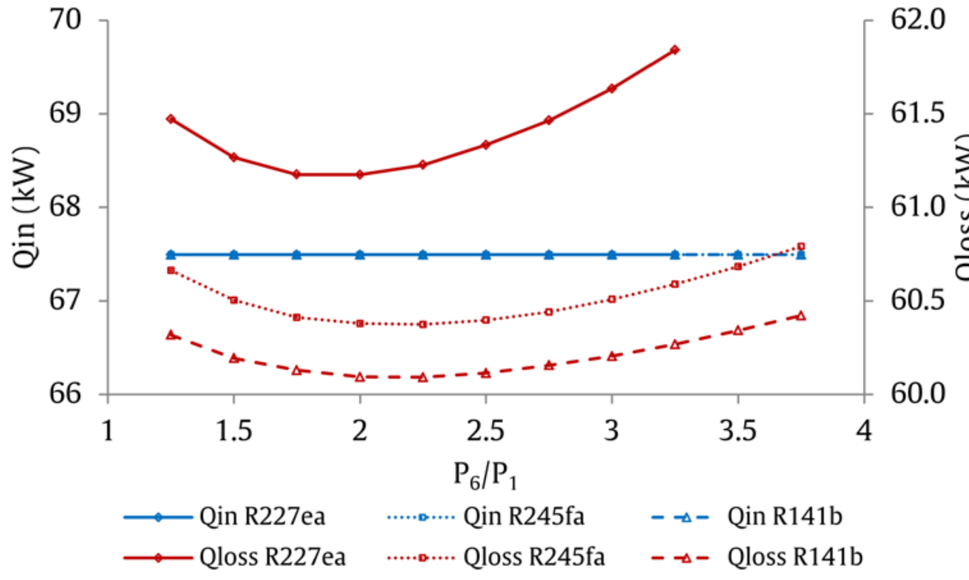

Figure 4. Q_{in} and Q_{loss} for each fluid atdifferent OFOH pressure

W_p obtained by R141b. Moreover, R141b obtains the highest Wt and R227ea obtains the lowest W_t.W_p for R227ea obtains the lowest and the highest result at P_6/P_1 = 3.25 and P_6/P_1 = 2.25, while W_t obtains its lowest and highest result at P_6/P_1 = 3.25 and P_6/P_1 = 2. R245fa and R141b obtain the highest and the lowest W_p at P_6/P_1 = 2.5 and P_6/P_1 = 3.75. Furthermore, the $W_t$value for R245fa and R141b obtain at P_6/P_1 = 2.25 and P_6/P_1 = 3.75 for the highest and the lowest W_t.W_p value for each state and each fluid are not significantly different, while for W_t, the middle ratio of P_6 and P_1 obtain the highest value, and the lowest value obtains from the highest P_6/P_1, which is close to inlet turbine pressure, thus made it gain the lowest W_t and W_p. The result of W_p and W_t are then used to determine the net power output (W_{net}) of the system, thus will obtain the energy performance of the system.

C. Net power output and thermal efficiency analysis

Net power output and thermal efficiency calculation are the final energy analysis. The result is shown in Figure 6. Figure 6 shows that W_{net} for R227ea obtains the highest result at P_6/P_1 = 2, R245fa and R141b at P_6/P_1 = 2.25. On the contrary, R227ea obtains the lowest W_{net} at P_6/P_1 = 3.25, and R245fa and R141b at P_6/P_1 = 3.75 obtain the lowest W_{net}. W_{net} value is influenced by the difference between W_p and W_t, which means that the higher W_t and the lower W_p obtain a high W_{net}. Figure 5 shows that W_p for R227ea obtains the lowest result at P_6/P_1 = 3.25, while W_t obtains its highest result at P_6/P_1 = 2. The result shows that W_{net} value is more influenced by W_t than W_p because W_{net} value results in the highest value at P_6/P_1= 2, which is the same as W_t.

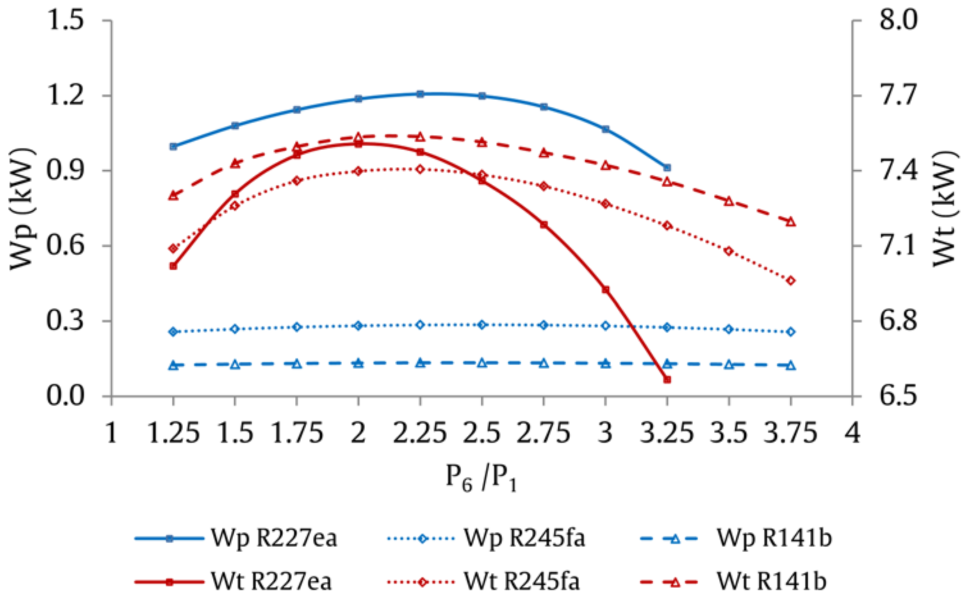

Figure 5. $W_p$and W_t for each fluid at different OFOH pressure

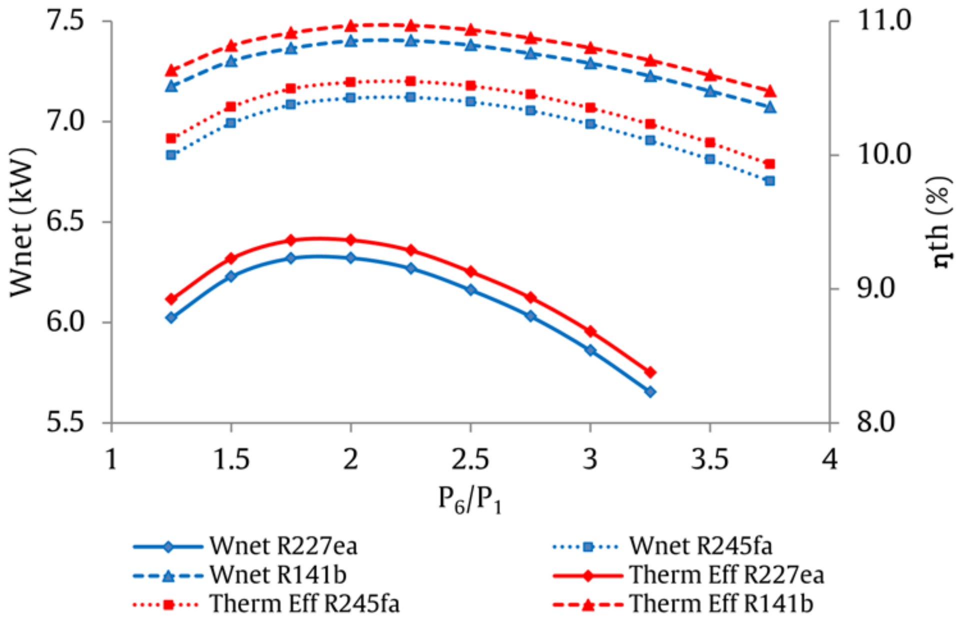

Figure 6. W_{net} and η_{th} for each fluid at different OFOH pressure

Furthermore, W_p value obtains a very low value compared to W_t , thus made W_{net} value more influenced by W_t than W_p. R245fa and R141b also obtain the highest W_{net} at P_6/P_1 = 2.25 because they obtain the highest W_t at the same P_6/P_1. However, R141b obtains the highest W_{net} value than R227ea and R245fa. The lowest W_p value obtained by R141b than R227ea and R245fa made R141b obtain the highest W_{net} since W_t value for each fluid almost obtain the same result in the same condition.

Thermal efficiency (η_{th}) value depends on heat input (Q_{in}) and W_{net} value. Since Q_{in} is the same for all fluids and all states, then η_{th} value depends on W_{net}. Equation (5) shows that the higher the W_{net} obtain a higher η_{th}. It is clear that Figure 6 shows the highest η_{th} value for R227ea obtained from P_6/P_1 = 2, the lowest η_{th} obtained from P_6/P_1 = 3.25, which is the same states with W_{net}. The result also the same with R245fa and R141b, where η_{th} value obtains its highest value at P_6/P_1= 2.25, and they obtain the lowest η_{th} at P_6/P_1 = 3.75, the same with W_{net} value. Furthermore, R141b obtain the highest η_{th} than R245fa and R227ea because R141b gain the highest W_{net} than other fluids. This result shows that R141b obtains the best energy performance than R227ea and R245fa.

D. Exergy input and exergy loss analysis

Exergy input and exergy loss are two main parameters for exergy analysis. The result of both parameters for three fluids in eleven states is shown in Figure 7. Figure 7 shows that all fluids obtain the highest Ex_{in} at the highest P_6/P_1, which is 3.25 for R227ea, and 3.75 for R245fa and R141b. In addition, the lowest Ex_{in} obtained from the lowest P_6/P_1,

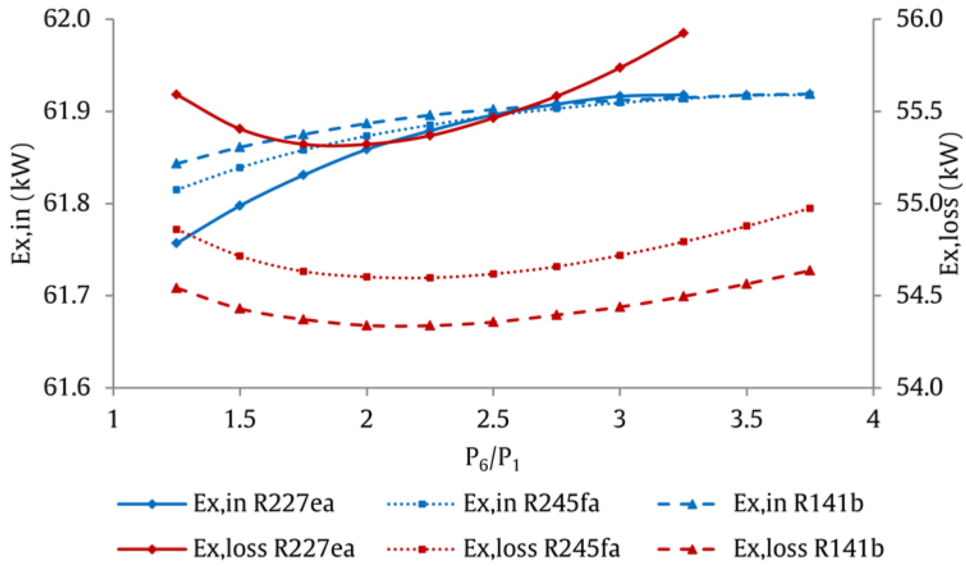

Figure 7. Ex_{in} and Ex_{loss} for each fluid at different OFOH pressure

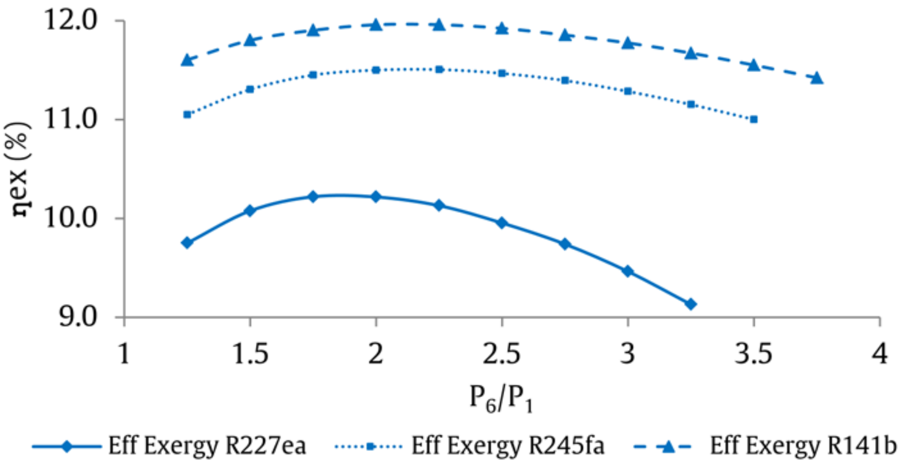

Figure 8. η_{ex} for each fluid at different OFOH pressure

which is 1.25. It can be analyzed that the highest pressure difference from P_1 and P_6 obtain the highest Ex_{in}. However, Ex_{in} value for all fluids at the same states obtain almost the same because of the same Q_{in} value for all fluids for all states. Figure 7 shows that R227ea obtains its highest and its lowest Ex_{loss} at P_6/P_1 = 3.25 and at P_6/P_1= 1.75. Similarly, R245fa and R141b obtain their highest and lowest Ex_{loss} at P_6/P_1 = 3.75 and at P_6/P_1 = 2.25. Ex_{loss} has a similar curve with the Q_{loss}, where it reaches the lowest P_6/P_1 in the middle and the highest P_6/P_1 at the highest value. The exergy input is then used to determine the exergy efficiency of the system.

E. Exergy efficiency analysis

Exergy efficiency is determined to perform the exergy performance of the system. Figure 8 shows the results for the three fluids in eleven states of OFOH in the SSRORC system. Figure 8 shows that η_{ex} obtains the highest value at P_6/P_1 = 1.75 for R227ea, nearly the same as at P_6/P_1 = 2, and at P_6/P_1 = 2.25 for R245fa and R141b. On the contrary, η_{ex} has the lowest value for R227ea at P_6/P_1 = 3.25, and for R245fa and R141b at P_6/P_1 = 3.75. The result is the same as η_{th}, where they obtain the highest value at the middle P_6/P_1 and the lowest value at the highest P_6/P_1. Although η_{ex} depends on W_{net} and Ex_{in} value, in this analysis the W_{net} result is more dominant than Ex_{in} for η_{ex}. Since Ex_{in} value is almost the same for all fluids and all states, the η_{ex} value has the same maximum and minimum value as W_{net} and η_{ex}.

IV. Conclusion

Open feed organic heater (OFOH) pressure analysis using eleven states obtain the best performance for R227ea at P_6/P_1 = 2 for energy analysis and at P_6/P_1 = 1.75 for exergy analysis, and at P_6/P_1 = 2.25 for R245fa and R141b. The lowest performance for R227ea was at P_6/P_1= 3.25, and at P_6/P_1 = 3.75 for R245fa and R141b. The analysis concluded that the P_6/P_1 in the middle value obtain the best performance, and the highest pressure difference from state 1 and state 6 obtain the lowest performance. R141b with the highest critical pressure than R227ea and R141b obtain the highest performance with thermal and exergy efficiency of 10.97 % and 11.96 %, thus made R141b is the most recommended fluid to be used for 100 °C of heat source temperature rather than R227ea and R245fa. Since in this paper it is assumed that a constant heat source temperature is used in analyzing the OFOH pressure influence to the SSRORC performance, the variation of the heat source temperature will be done in the future to complete the analysis of OFOH pressure to the performance of SSRORC.

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Declarations

Author contribution

G. Pikra is the main contributor of this paper. All authors read and approved the final paper.

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Conflict of interest

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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