Journal of Research and Applications in Mechanical Engineering
ISSN: 2229-2152 (Print); 2697-424x (Online)
(2020) Vol. 8, No. 2, 101-113
DOI: 10.14456/jrame.2020.12

Research Article

WASTE HEAT RECOVERY POWER PLANT FOR A HEAT SOURCE TEMPERATURE OF 130 - 150°C

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Received 6 November 2019
Revised 20 December 2019
Accepted 24 December 2019

ABSTRACT:
Organic Rankine cycle (ORC) is a promising technology for power generation that uses low-temperature heat from various sources including renewable energy and waste heat. The objective of this study is to design thermodynamically a subcritical ORC, supercritical ORC, and trilateral Rankine cycle (TLC) power plants that can provide the highest net power output when the heat source temperature is 130 - 150°C. A numerical model was developed using MATLAB. The thermophysical properties of the working fluids studied are calculated by NIST REFPROP program. The simulations show that the subcritical plant with RC318 as its working fluid provides the highest net power when the heat source temperatures are at 130°C and 140°C. The corresponding net powers are 15.6 kW and 23.08 kW, respectively. While one with perfluoropentane as it working fluid provides the highest net power when the heat source temperatures is at 150°C and the net power is 26.3 kW. The supercritical plant with R1216 as its working fluid provides the highest net power of 17.1 kW when the heat source temperatures is at 130°C. Meanwhile the plant with RC318 as its working fluid provides the highest net power of 24.2 and 31.5 kW when the heat source temperatures are at 140°C and 150°C, respectively. On the other hand, the TLC power plant with perfluoropentane as its working fluid provides the highest power output over the whole range of the heat source temperature studied. Its corresponding power output are 21 kW, 27.2 kW, and 34.5 kW, respectively. Additionally, the off-design simulations when the heat source temperatures were varied in the range of 125 - 155°C were conducted and it was found that a proper adaptation of the operating conditions (evaporation and condensation pressures, working fluid flow rate) can maintain a constant power output.

Keywords: *subcritical ORC, supercritical ORC, trilateral Rankine cycle, waste heat*

1. INTRODUCTION

The Alternative Energy Development Plan: AEDP2015 [1] reported that heat energy form is the most utilized renewable energy that more than 60 percent for the use of all renewable energy, followed by biofuel and electricity. In 2014, energy consumption was accounted for 64 percent, biofuels and electricity accounted for 19.7 percent and 16.3 percent, respectively.

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The Organic Rankine cycle (ORC) is a promising waste heat recovery technology. This cycle used organic working fluids characterized by a low boiling point and constant temperature during their phase changing processes [2, 3]. However, one of the main problems in ORC power plants is the high exergy destruction in these cycles. The main source of problems occurred in evaporator because of the temperature mismatching between the source and the working fluid [4, 5].

In terms of ORC applications, subcritical used in normal ORC, which assumes the state of working fluid at evaporator outlet is saturated vapor and uses configurations as well as Rankine cycle [6, 7]. In addition, many researchers have been developed concepts to enhance the electricity generation for geothermal heat sources and have been developed by used regenerative ORC with low-temperature heat sources [8, 9].

Moreover, supercritical ORC is one of ORC applications that can increase the exergy efficiency of ORC. However, configurations in this cycle must be stronger than subcritical and state of working fluid that through expander is saturated liquid-vapor mixture. Furthermore, the temperature of working fluid at the evaporator output is higher than the critical temperature of its [10].

The last application will be shown is the trilateral Rankine cycle. Researchers have been developed and improved to enhance net power output and cycle efficiency from normal ORC [9]. This cycle is used in low-temperature heat sources. It's can enhance net power output and thermal efficiency better than subcritical ORC. The difference between it and subcritical ORC is the state of working fluid at the evaporator outlet, it's saturated liquid and working fluid temperature is lower than critical temperature [11, 12].

From the term of ORC applications that researchers have been predicted and improved can be interested in design and investigate about this cycle by select working fluid for each application. Conditions for simulation will be selected working fluid that can generate maximum net power output for heat sources temperature at 130, 140, and 150℃, respectively. Then, the author will design applications when heat sources and cooling fluid temperature changed. All the concepts will be produced and improved by used MATLAB with NIST REFPROP for analyzing the influence of the mass flow rate of the working fluid and the pressure that the evaporator and condenser generate the highest net power output at various heat source temperatures.

Thus, the objective of the Organic Rankine cycle power plant is to be selected the working fluid that can achieve the highest net power output at the heat source temperatures is 130 - 150℃.

2. RESEARCH METHODOLOGY

2.1 Conventional ORC description

In this paper, configurations in cycles consist of pump, evaporator, expander, and condenser illustrate in Fig. 1 is considered. The working fluid is entered pump as saturated liquid (point 1), is pumped to higher pressure. Then, it is entered evaporator to heat with heat sources (heating fluid) at constant pressure (point 2). Next, it is entered turbine to generate power (point 3) and is went to condenser for condense working fluid before entering pump again (point 4).

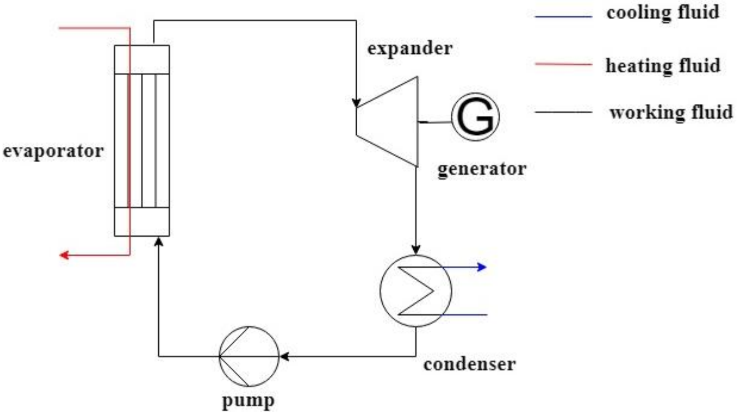


Fig. 1. Configuration of Organic Rankine cycle.

2.2 Subcritical ORC description

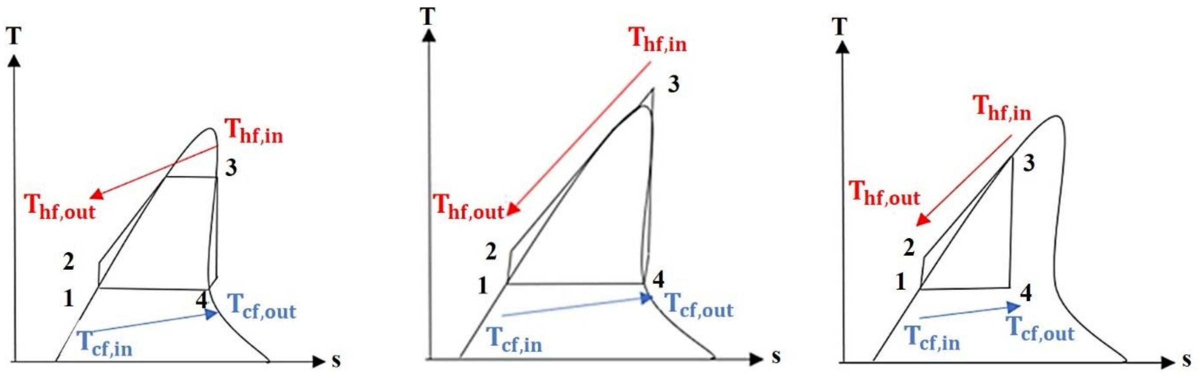
Subcritical ORC is similar to conventional ORC. It's simple and easy to build configurations when compared with other applications. From T-s diagram in Fig. 2(a) was shown the working fluid line in cycle (black line). Heat source and cooling fluid are red line and blue line, respectively. In state 1 the working fluid is saturated liquid was pumped to higher pressure at state 2. In state 2 the working fluid in evaporator is constant pressure until in state 3 at saturated vapor. Then, working fluid has decreased the temperature in expander and was condensed at state 4 in condenser before entered in pump (state 1) again.

2.3 Supercritical ORC description

Supercritical ORC is different from subcritical ORC at state 3 which T-s diagram was shown in Fig. 2(b). In state 3 working fluid temperature is higher than critical temperature of working fluid that can be decided working fluid state in expander is superheated vapor.

2.4 Trilateral Rankine cycle description

In the trilateral Rankine cycle (trilateral RC) at state 3 working fluid is saturated liquid was shown in Fig. 2(c) and the temperature of state 3 is lower than the critical temperature of its. It was damaged in blades of expander because it has a saturated liquid-vapor mixture in expander. Therefore, the expander should be built to have a stronger or larger blade than other cycles. While working fluid was left from expander, it was entered condenser as a saturated liquid-vapor mixture (point 4 in Fig. 2(c)) that different points from other applications.



(a) (b) (c)

Fig. 2. T-s diagram of (a) subcritical ORC (b) supercritical ORC (c) trilateral Rankine cycle.

2.5 Theorical and equations

In this paper, thermodynamics analysis was carried out and calculated by MATLAB. Net power output equations for cycle can be defined as

$$W_{net} = m_{wf} \times w_{net} \tag{1}$$

where $w_{net} = w_t \times w_p$ (2)

From the conservation of energy, energy enters the system is equal to energy leave from system. Thus, the energy that entered and left in pump and expander was considered. Equations of work in these configurations were calculated by referring to Fig. 1 as

$$w_p = h_2 - h_1 \tag{3}$$

and $w_t = h_3 - h_4$ (4)

Furthermore, the system has thermal energy occurred in evaporator and condenser. So, the system was calculated thermal energy in and thermal efficiency of system by

$$Q_{in} = m_{wf}(h_3 - h_2) \quad (5)$$

$$Q_{out} = m_{wf}(h_4 - h_1) \quad (6)$$

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad (7)$$

3. MATHEMATICAL MODEL

3.1 Assumptions

In this paper, author designed a mathematical model of cycle based on the first and second laws of thermodynamics are required as follows:
- The working fluid at inlet pump is a saturated liquid state (point 1 in Fig.1).
- Conservation of mass equations in all configurations is considered.
- Pinch point temperature between heat sources and working fluid in evaporator and between heat sink and working fluid in condenser is 10°C.
- The friction loss and pressure loss in configurations are negligible.
- The energy loss in process is negligible.
- Water is heating fluid (heat sources) and cooling fluid (heat sink). Its pressure is 10 bar.
- Configurations consist of a pump, an evaporator, an expander, and a condenser.
- An evaporator and a condenser used the counter-flow heat exchangers.

Initial conditions for cycles was follow parameters in Table 1.

3.2 Working fluid selection

A simulation was carried out by using MATLAB version R2017a with NIST REFPROP 9.1 [13]. NIST REFPROP was used for calculation of the working fluid's properties. In order to simulate cycles, we must select working fluid for each cycle and each heat source temperature. The principle for select working fluid is considered, its critical temperature nearly heat sources temperature. Then, selected its critical temperature increase or decrease from the previous working fluid at 5°C until the working fluid can generate the maximum net power output.

3.2.1 Subcritical ORC simulation

Working fluids are selected under conditions in this simulation have 16 working fluids that show properties in Table 2.

3.2.2 Supercritical ORC simulation

Working fluids are selected under conditions in this simulation referred [14]. Principle for select is critical temperature is lower than heat source temperature about 30-50°C [14]. So, this simulation has 10 working fluids that show properties in Table 2.

3.2.3 Trilateral RC simulation

Working fluids are selected under conditions and referred to as Fig. 2 (c). So, working fluids in this simulation have 18 working fluids that show properties in Table 2.

3.3 Flowchart

From concept for design cycle, flowchart will be shown concept for simulate in Fig. 3(a). However, author studied for situations that heat source and cooling fluid temperature are variable if used the same condenser and evaporator from design, was called off-design.

Off-design concept will use working fluid can be generated net power output at each simulation from design. This concept will be a fixed size of condenser and evaporator when heat source and cooling fluid temperature are variable.

Table 1: Initial conditions were assumed in cycles.

Parameters	Value
Pressure of heat source (bar)	10
Pressure of cooling fluid (bar)	10
Isentropic efficiency of pump	0.75
Isentropic efficiency of expander	0.8
Mass flow rate of heat source (kg/s)	1
Inlet temperature of cooling fluid (℃)	30
Pinch point temperature (℃)	10

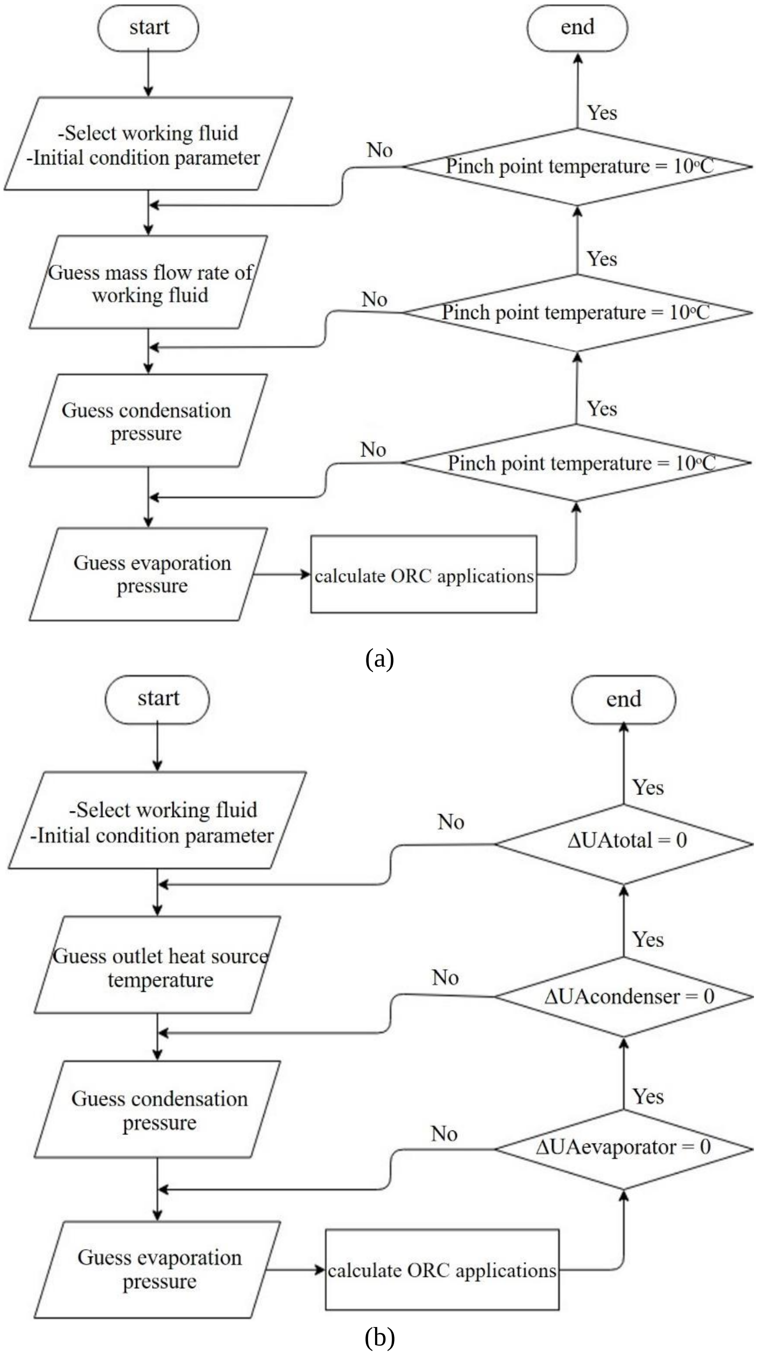


Fig. 3. Flowcharts for (a) design ORC operations (b) off-design ORC operations.

Table 2: Properties of working fluids [13].

working fluid	type	critical temperature (°C)	critical pressure (MPa)	applications		
				subcritical ORC	supercritical ORC	trilateral RC
carbonyl sulfide	wet	105.62	6.370	x	x	x
R1234ze	isentropic	109.36	3.635	x	x	x
RC318	dry	115.23	2.778	x	x	x
R124	dry	122.28	3.624	x	x	-
R236fa	dry	124.92	3.200	x	x	x
propyne	wet	129.23	5.626	x	x	x
isobutane	dry	134.66	3.629	x	-	x
R236ea	wet	139.29	3.420	x	-	x
R114	dry	145.68	3.257	x	-	x
perfluoropentane	dry	147.41	2.045	x	-	x
R245fa	dry	154.01	3.651	x	-	x
neopentane	dry	160.59	3.196	x	-	x
R1233zd	dry	165.60	3.570	x	-	x
RE245fa2	dry	171.73	3.433	x	-	x
R245ca	dry	174.42	3.940	x	-	x
R218	dry	71.87	2.640	-	x	-
R115	dry	79.95	3.129	-	x	-
R1216	dry	85.75	3.150	-	x	-
R1234yf	dry	94.70	3.382	-	x	-
R21	wet	178.33	5.181	x	x	x
R365mfc	dry	186.85	3.266	x	x	x
pentane	dry	196.55	3.370	x	x	x
R11	isentropic	197.96	4.408	x	x	x

4. Results and Discussion

4.1 Validation of ORC simulations

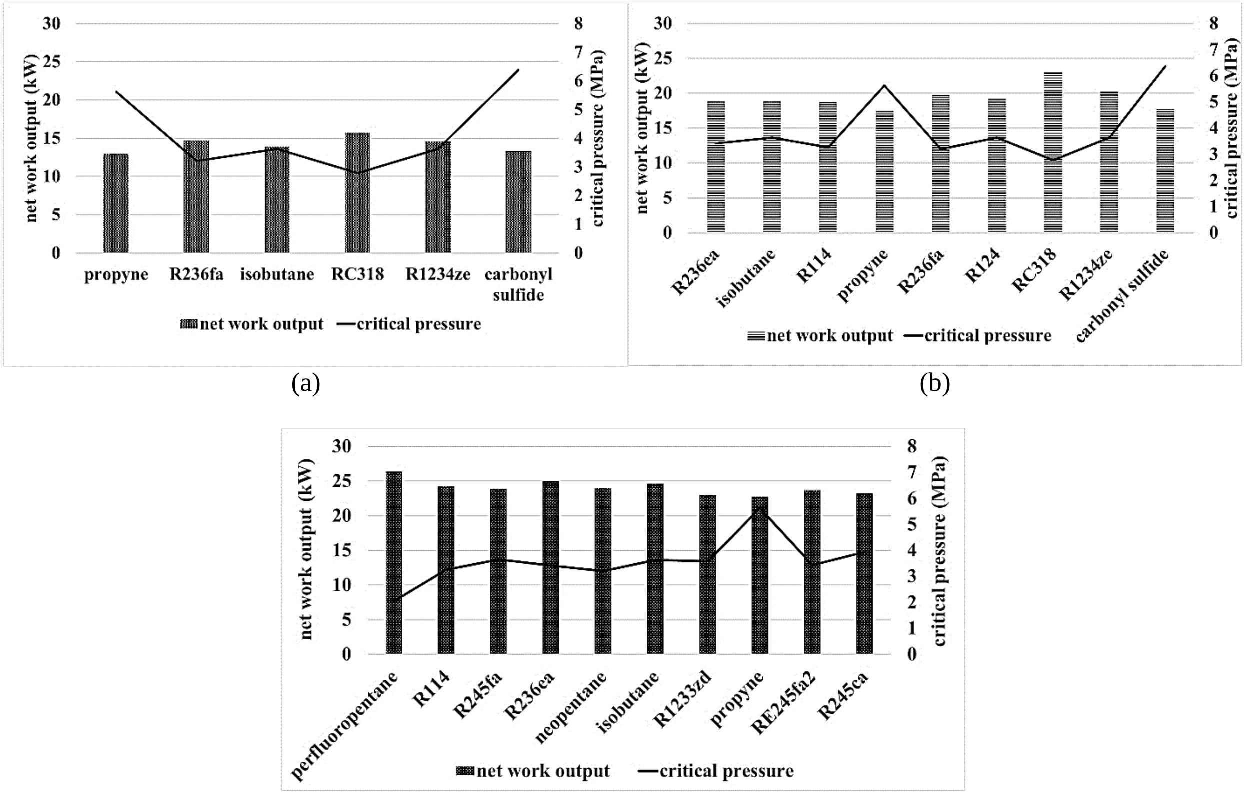
To check the accuracy of the program, the author simulated the program with [12]. The results can be shown in Table 3.

Table 3: Validation results.

Parameter	ORC simulations					
	subcritical ORC		supercritical ORC		trilateral RC	
	[12]	present study	[12]	present study	[12]	present study
Pump inlet temperature (K)	358.150	358.350	358.150	358.350	358.150	358.151
Expander outlet temperature (K)	396.410	396.030	401.000	404.040	358.150	358.151
Outlet heat source temperature (K)	408.700	407.120	394.290	394.350	370.530	370.468
Outlet cooling fluid temperature (K)	348.85	349.03	348.94	348.94	348.15	348.15
Rate of heat transfer inlet evaporator (kW)	5790.00	5853.00	5368.00	5365.40	5054.00	5053.60
Rate of heat transfer outlet condenser (kW)	4790.00	4853.00	4368.00	4365.40	4054.00	4053.60
Thermal efficiency	0.173	0.171	0.186	0.186	0.198	0.198

4.2 Results of subcritical ORC simulation

From the design using the parameters specified by the working fluid according to Table 2 can show the ability to produce the maximum net power output of the heat source at 130°C, 140°C, and 150°C as shown in Fig. 4 (a), (b), and (c), respectively.



(a) (b) (c)

Fig. 4. Highest net power output of various working fluid at (a) 130°C, (b) 140°C, and (c) 150°C for the subcritical ORC plant.

According to Fig. 4, the working fluid that can be produced the maximum power at 130 - 140°C is RC318 which can be produced 15.66 kW at mass flow rate of 2 kg/s and 23.09 kW at mass flow rate of 2.4 kg/s, respectively. And perfluoropentane can be produced at a maximum temperature of 150°C which can be produced 26.36 kW at mass flow rate 2.7 kg/s.

When considering all 3 working fluids, it was found the dry type working fluid has the lowest critical pressure and less critical temperature from heat source temperature about 3 - 30°C. It can be produced the highest net power. However, the size of the evaporator and condenser will be large to generate the maximum power.

4.3 Results of supercritical ORC simulation

From the design using the parameters specified by the working fluid according to Table 2, the maximum power capacity of the substance can be displayed, working at 130°C, 140°C, and 150°C as shown in Fig. 5 (a), (b), and (c), respectively.

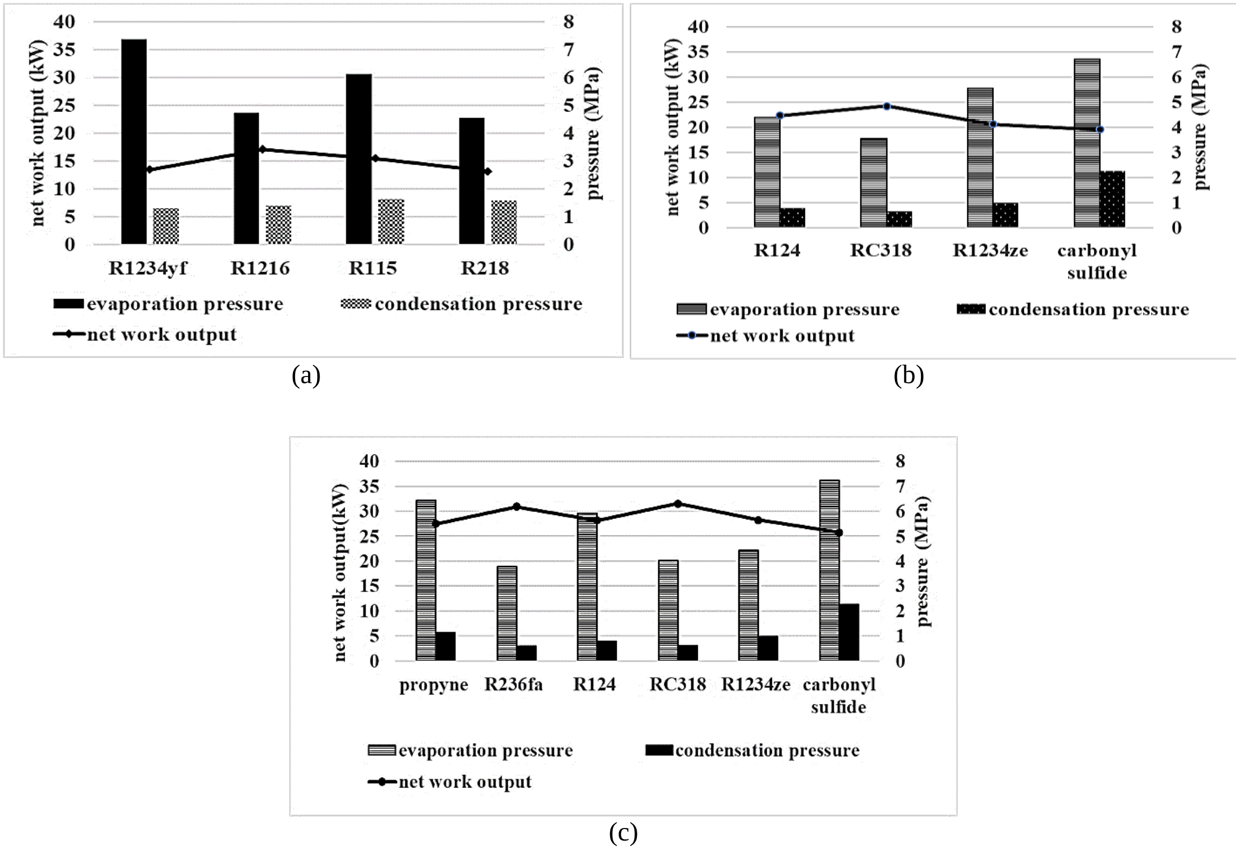


Fig. 5. Highest net power output of various working fluid at (a) 130°C, (b) 140°C, and (c) 150°C for the supercritical ORC plant.

According to Fig. 5, the horizontal axis is working fluids that are considered at various temperature ranges, the primary vertical axis is the net power output and the secondary vertical axis is the pressure that is used within the evaporator and condenser. The results were found the maximum net power output received at 130°C is the R1216. It can be produced 17.14 kW at mass flow rate of 2.7 kg/s and uses evaporation and condensation pressure to 4.7 and 1.4 MPa compared with the substances being considered in the same heat source temperature. However, the size of the configurations will be large when compared with the working fluids in the same temperature range.

As for the temperature range of 140-150°C, the working fluid that can be produced the maximum net power output is R318. The power can be produced at the temperature range of 24.27 and 28.18 kW, respectively. The mass flow rate is 2.9 kg/s and the evaporation and condensation pressure are 3.5 and 0.6 MPa, respectively. And at 150°C the mass flow rate is 3.3 kg/s and the evaporation and condensation pressure are 4 and 0.63 MPa, respectively.

Therefore, it can be considered that the substance that produces the highest net power output will have the least evaporation pressure compared to the working fluids that are considered at the same temperature. And the working fluid that can produce maximum net power output must have a critical temperature below 25-45°C.

4.4 Results of trilateral RC simulation

From the design using the parameters specified by the working fluid according to Table 2, can show the ability to produce the maximum net power output of the working fluid at 130°C, 140°C, and 150°C as shown in Fig. 6 (a), (b), and (c), respectively.

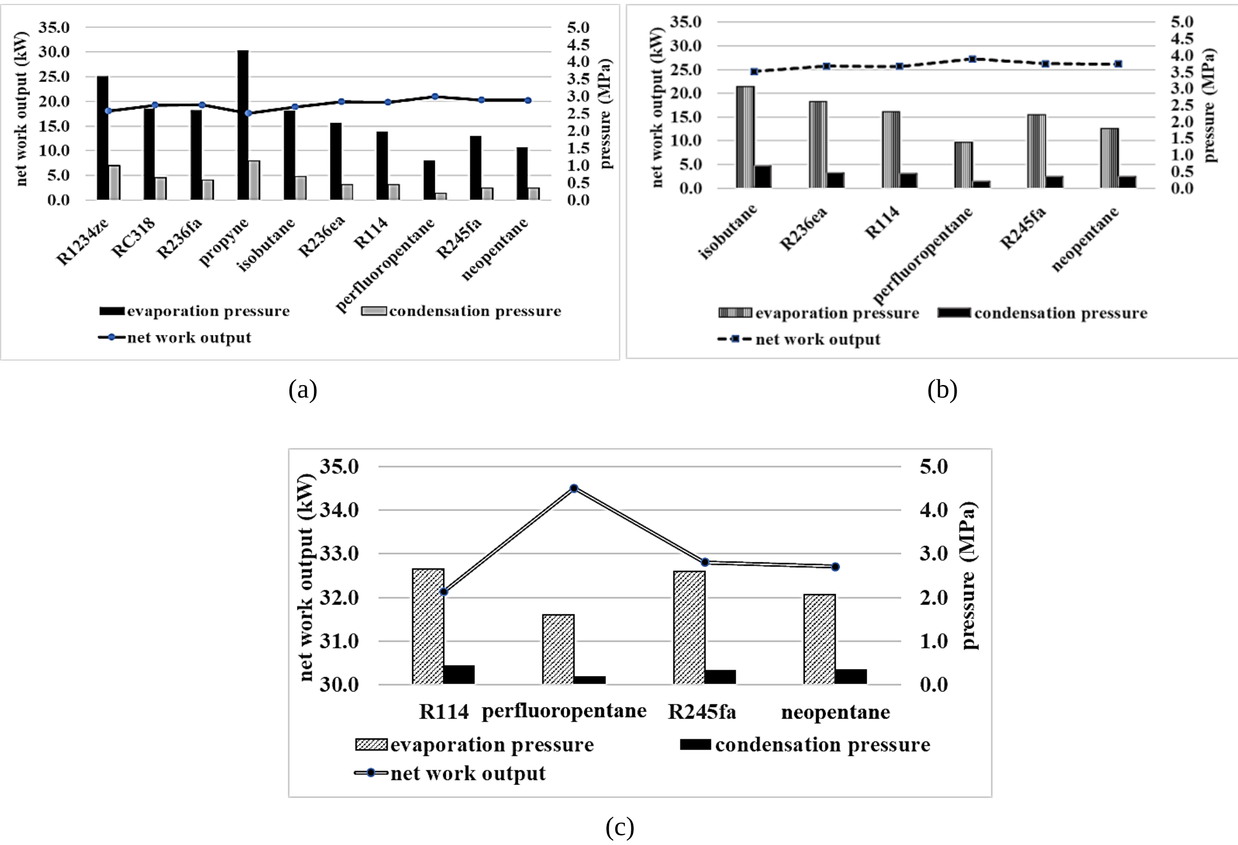


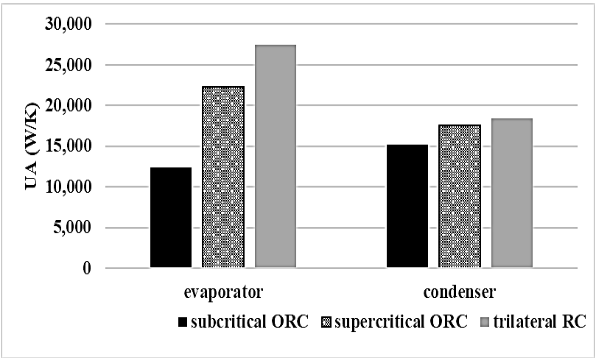
Fig. 6. Highest net power output of various working fluid at (a) 130°C, (b) 140°C, and (c) 150°C for the trilateral plant.

According to Fig. 6, it was found that the working fluid can produce the maximum power output at a temperature range of 130 - 150°C is perfluoropentane. It can produce 21, 27.23, and 34.5 kW, respectively, by using a mass flow rate of 3.5 kg/s at all temperature heat sources. And the pressure of the evaporator and condenser at 130°C are 1.1 and 0.2 MPa, respectively, at 140°C are 1.38 and 0.2 MPa, respectively, and at 150°C are 1.6 and 0.195 MPa, respectively.

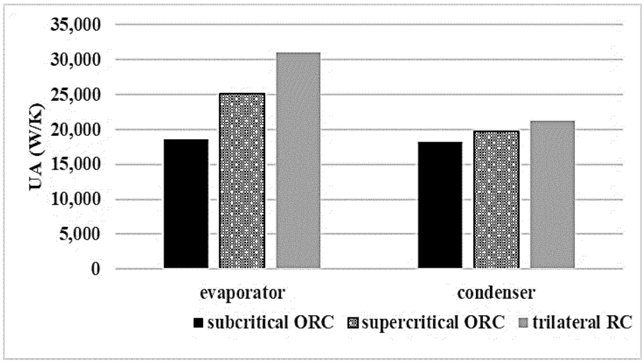
The working fluid that can produce net power output in this simulation will have more critical temperature than the heat source temperature. Because when the substance is working inside the evaporator will try to adjust the pressure and temperature to allow the pinch point temperature to be 10°C, as well as considering Fig. 2 (c) at position 3 or the expander entrance is the area that may cause pinch point temperature.

Therefore, the working fluid with a critical temperature higher than the heat source temperature allows its temperatures to be closer to the temperature of the heat source than the fluids with lower critical temperatures can do.

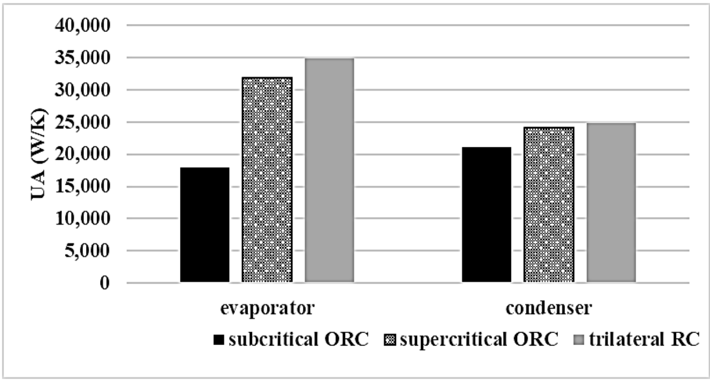
According to maximum net power output each application was found trilateral RC application can be produced the maximum net power output. However, evaporator and condenser in cycle will be strong and bigger than subcritical ORC and supercritical ORC for produce net power under conditions. The results were shown in Fig. 7.



(a)



(b)



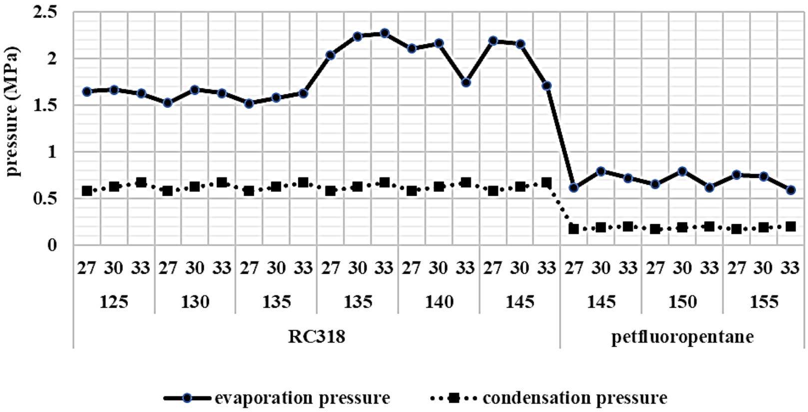
(c)

Fig. 7. Overall heat transfer per area in evaporator and condenser at variable heat source temperature (a) 130°C (b) 140°C (c) 150°C.

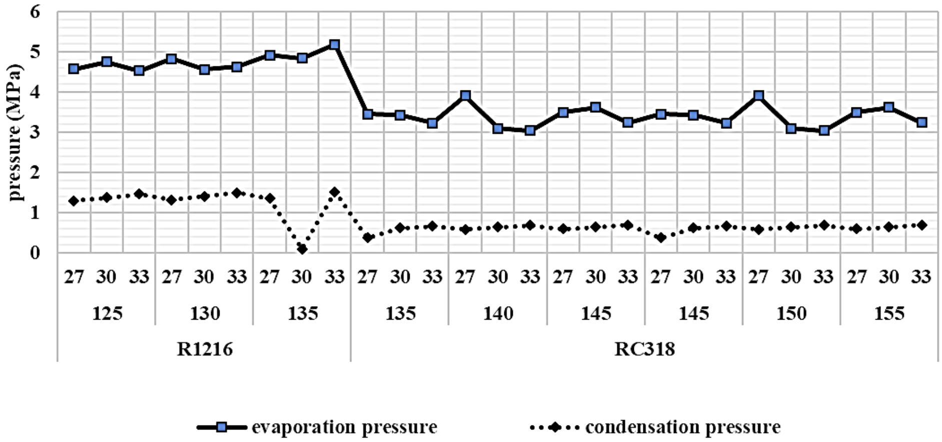
4.5 Results of off-design simulations

From the design to select the working fluid that produces the highest net power output of all 3 cases, select the working substance that produces the highest net power output to be simulated outside the conditions designed to study the pressure of the evaporator and condenser when the heat source and cooling fluid temperature change can show simulation results in subcritical, supercritical, and trilateral cases as shown in Fig. 8 (a), (b), and (c), respectively.

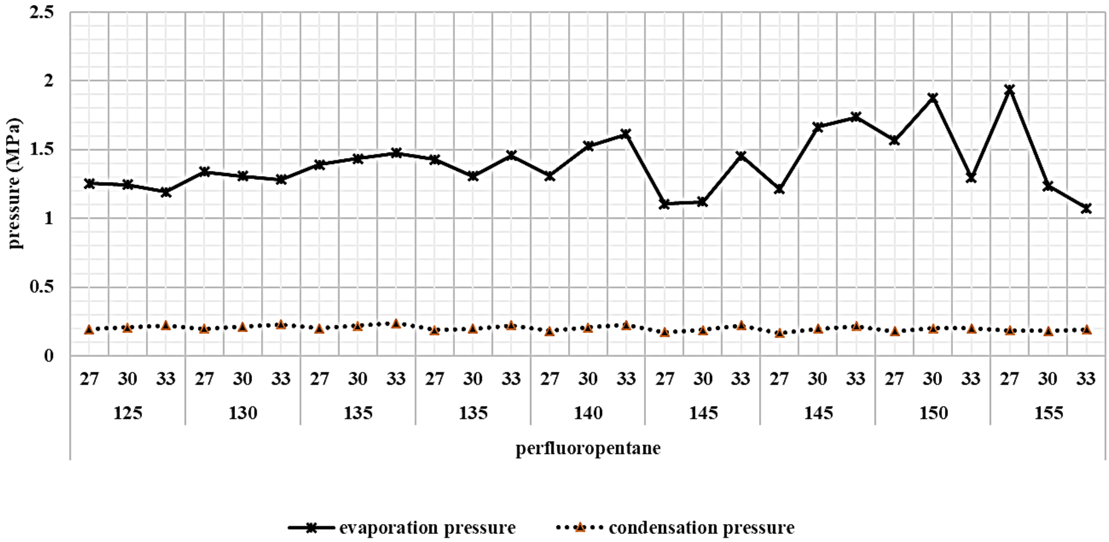
From the off-design design of the 3 simulations, by changing the heat source temperature to 125-155°C and the cooling fluid temperature is 27, 30, and 33°C to study the pressure generated within the configuration. If there is no exact evaporation pressure trend, because the work substance will try to adjust the pressure in order to be able to produce the highest net power output and the condensation pressure is not changed from the designed value.



(a)



(b)



(c)

Fig. 8. Evaporation and condensation pressure at variable heat source temperature for the (a) subcritical ORC (b) supercritical ORC (c) trilateral RC.

5. Conclusion

In this paper, the performance of a subcritical ORC, supercritical ORC, and trilateral RC with the heat source temperatures of 130 - 150°C were analyzed. Several working fluids for each plant were examined. It was found that:

The subcritical ORC plant with R318 as its working fluid provides the highest net power output of 15.66 kW and 23.09 kW when the heat source temperature is at 130 and 140°C, respectively. Meanwhile, the subcritical plant with R1216 which can produce as its working fluid provides the highest net power output of 26.36 kW when the heat source temperature is at 150°C.

The maximum net power outputs for the supercritical plant are at 17.14 kW, 24.27 kW, and 28.18 kW when the heat source temperature is 130, 140, and 150°C, respectively. While the corresponding values for the trilateral plant with perfluoropentane as its working fluid provide 21, 27.23, and 34.5 kW, respectively.

It was also found that the working fluids for the subcritical plant that provide the maximum net power output have their critical temperature 3 until 30°C below the heat source temperature. While the optimal working fluid for the supercritical plant has its critical temperature 25 until 45°C below the heat source temperature.

Acknowledgment

Thank you to Kitti Bundit scholarships, Suranaree University of Technology for granting scholarships for research work.

Nomenclature

h	enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
Q_{in}	rate of heat transfer at evaporator (kW)
Q_{out}	rate of heat transfer at condenser (kW)
T_{in}	inlet temperature (°C)
T_{out}	outlet temperature (°C)
UA	overall heat transfer per area (W/K)
w_{net}	net power output per mass flow rate (kJ/kg)
$\dot{W}_{net}$	net power output (kW)
w	work (kJ/kg)
η_{th}	thermal efficiency

Subscripts

cf	cooling fluid
hf	heating fluid
p	pump
t	turbine
wf	working fluid

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