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Research Article

FLUID SELECTION AND OPTIMAL OPERATING CONDITIONS OF AN ORC, AND TRILATERAL RANKINE CYCLE POWER PLANT FOR A HEAT SOURCE TEMPERATURE OF 210°C - 250°C

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ABSTRACT:
A selection of an appropriate working fluid for electricity production using a heat source of 210°C - 250°C was conducted. Three types of power plants were examined. They are a subcritical ORC (organic Rankine cycle), supercritical ORC, and trilateral Rankine cycle (TLC) power plants. An optimal operating condition for each working fluid and each power plant type was searched by using the golden section search method. A MATLAB code was developed and used in this simulation. The thermodynamic properties of the working fluids were calculated by using NIST REFPROP program. The justification of the code was validated with a result taken from the literature. The maximum net output was obtained when using the supercritical ORC plant with R141b as its working fluid and the heat source temperature is at 250°C. That plant produces a power of 141.72 kW and the cycle efficiency is 16.25%. The maximum net power output of 133.40 kW and cycle efficiency of 15.70% are obtained from the subcritical plant with pentane as its working fluid and is used as the working fluid and the heat source temperature is also at 250°C. Moreover, the net power outputs of 133.82 kW and cycle efficiency of 14.90% are obtained when using R141b as the working fluid in the TLC power plant. According to the off-design simulations, an appropriate adjustment of the working fluid flow rate can regulate the net power output.

Keywords: *subcritical ORC, supercritical ORC, trilateral Rankine cycle, thermodynamic optimization, working fluid selection*

1. INTRODUCTION

Generally, fossil fuels such as petroleum, coal, and natural gas are used to produce electricity [1]. 19% of electricity in Thailand were produced from coal in 2013. It was found that electricity production by coal causes high air pollution such as sulfur dioxide that made acid rain [2] and [3].

Present have a cycle use for electricity produce from waste heat. That cycle will use waste heat be heat source also known as the organic Rankine cycle (ORC). A working fluid of ORC often use low bowling temperature for example R410a and R407c etc. [4]. Which electricity production is pollution less [5].

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In Thailand have waste heat 65.3% from total waste energy from 2015 energy report of Thailand. That energy will be solar energy, biomass, biogas and refuse [6]. Those energy can be renewable energy of heat source for ORC cycle that produce electric.

Currently have topic research of supercritical ORC [7]. Frist have simulation about heat source temperature 70°C - 230°C from Rankine cycle waste heat, the maximum net power output is 220 kW and have studied of [8] is about using natural gas for heat source for supercritical ORC, the maximum net power output is 81.52 kW. More over some researcher studied supercritical ORC by linear Fresnel reflector solar concentrator be heat source for cycle the maximum is 190.5 kW, heat source temperature is 150°C - 350°C [9].

In addition to the ORC cycle It also has a subcritical supercritical well as the use of work R1234ze the heat source temperatures 100°C - 200°C The results were equal to the highest power 85 kW [10]. Have studied the waste heat from roasting coffee the waste heat of roasting has a temperature of 120 ° C. The results showed that the energy obtained was 26.6 kW using the R227ea be work [11]. And the study of the use of waste heat from the engine to be used in electricity production. The results of the study show that the maximum electrical energy can be produced is 2.56 kW for the engine with brake power equal to 93 kW [12].

And there is another type we call more than the trilateral ORC, which in the study of [13] simulates the use of the trilateral ORC at a heat source of 120°C. The maximum net power is 2.3 MW using isobutane as a working fluid. The thermal efficiency is equal to 8.16%.

In actual working conditions, we cannot force the environment and the heat source to be fixed as designed because the heat source and environment can be changed which results in the system being unable to function, such as Therefore, the system should be able to adjust according to the environment. And the heat source to maintain the work that the system will provide the same by calling the process as off design. Such designs have been studied, such as the study of Benito at al. Has shown that the change of heat source varies directly, resulting in a cyclical energy that can be achieved Where, if the heat energy of the heat source increases, it will increase the energy from the cycle [14] and the studies of Cao and Dai show that the work energy, higher heat sources, including the environment temperature Higher will make more work [15].

From the above, the waste heat can be used to produce electricity using the ORC cycle and must consider the environment as well as the heat source that has changed. Discarding blades for further study of energy saving, leaving at 210°C - 250°C returned to use in the production of electricity in order to maximize the benefits of energy use and the conversion of values in the ORC cycle system when the heat source changes to the system and weather conditions in order to get the same net electricity.

2. METHODOLOGY

2.1 Selection of working fluid

In the simulation system, the principle of selecting the working fluid that is suitable for the temperature is 210°C, 230°C, and 250°C. Supercritical ORC will choose to work with a temperature below 30°C to 50°C according to the study of Hærvig et al [16]. And in the selection of subcritical ORC workflows, the principle of selecting working fluid to be chosen is to have a temperature close to the temperature of the heat source [17] and in the trilateral ORC select work working fluid Which will find the selection of working fluid from the simulation as Table 1.

2.2 Design system

The simulation of the system consists of three systems: the system of subcritical, supercritical and trilateral ORC cycle. The thermal equipment used in the cycle is as shown in Fig. 1.

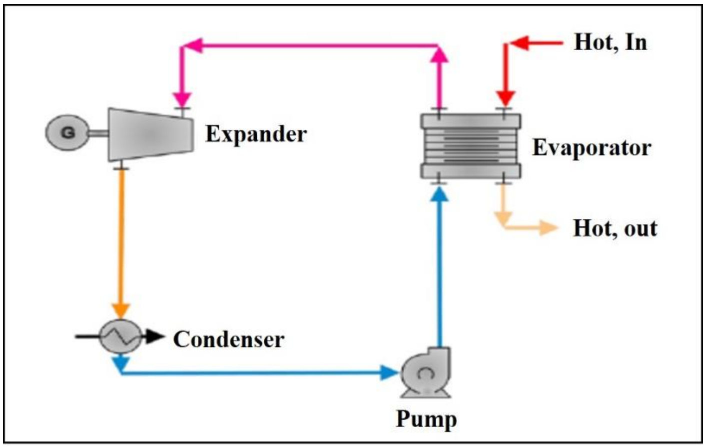


Fig. 1. Schematic diagram of ORC cycle [14]

The characteristics of the T-s diagram of the subcritical, supercritical and trilateral systems are shown in Fig. 2(a), 2(b) and 2(c).

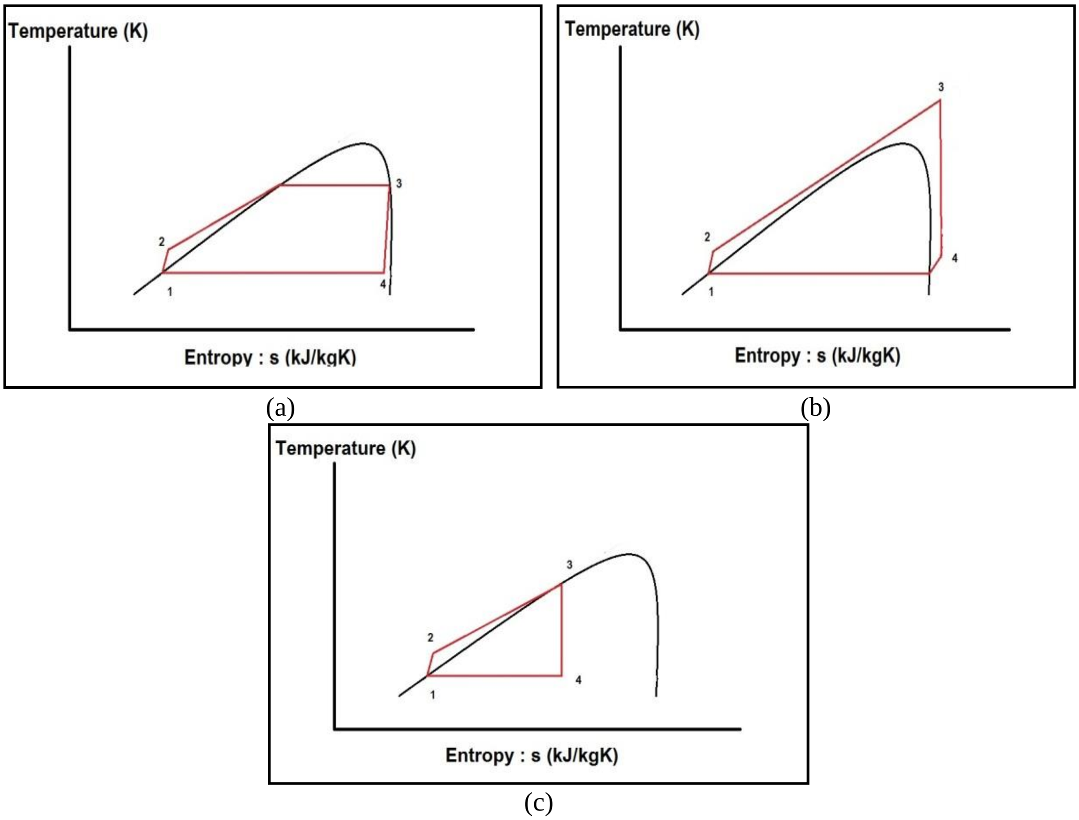


Fig. 2. T-s diagram of (a) subcritical ORC, (b) supercritical ORC and (c) trilateral cycle

The simulation of the ORC cycle will be used to determine the water been heat source, the temperature of heat source is 210°C, 230°C and 250°C at the flow rate of 1 kg/s and the cooling water inlet temperature is 30°C and when absorbed heat from system, the temperature will be 40°C, which is the highest net power at pinch point temperature equals 10°C (K) $\eta_{isen,p} = 0.75$, and $\eta_{isen,t} = 0.80$ is suggested by [18]. Design of the ORC cycle system using MATLAB and NIST REFPROP program development the simulation of the simulation process will be as follows Fig. 3(a).

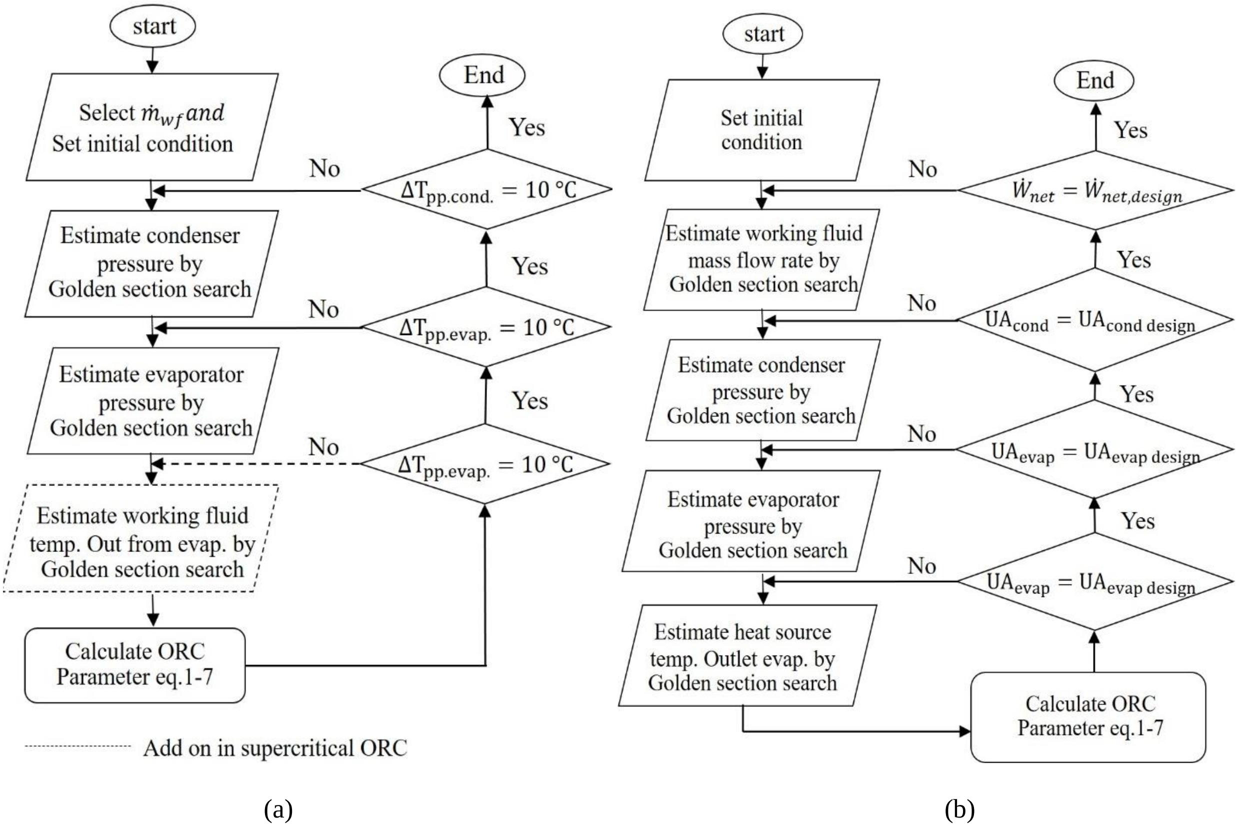


Fig. 3. Flowchart for the (a) design and (b) off-design simulations

From Fig. 3(a), the simulation of the ORC cycle by simulation is required to determine the edge of the answer, whether the pressure at the condenser and the evaporator, as well as the temperature of the working fluid at evaporator outlet in supercritical case by golden section search method to find the answer and check whether the ΔT_{pp} of each device is close to 10°C or not. If it is closed, then the answer is then bringing the answer in each flow rate of the working fluid. Then vary flow rate for find maximum work each working fluid.

2.3 Off-design system

The off-design process will select the working fluid that interesting work. Then simulate the environment and the temperature of the heat source changes. At the temperature of the heat source changes ±5°C and gives the temperature of the cooling water ± 3°C, allowing the work from the cycle to be the same value from the designed values, including the UA value of the heat exchanger Then give the pressure value at condenser, the pressure at the evaporator, the temperature of the working fluid released from the evaporator, pinch point temperature, and other values With the off-design simulation process, the ORC cycle system will use the MATLAB and NIST REFPROP program to simulate the simulation process to be as follows Fig. 3(b).

From Fig. 3(b), it is a simulation of the ORC, which requires the use of the UA variable of the system as if it were designed by changing the temperature of the environment, such as temperature, heat source and temperature. The system adjusts itself to get the same network.

By starting to simulate the system that when the off-design condition occurs, how will it affect the system by defining the initial values such as the UA value of the heat exchanger, the flow rate of the working fluid and the coolant, etc.

and then find the work value obtained from the system and study the effects will then change the flow rate of the system to get the job equal to the value of the designed work..

2.4 Mathematical modeling

The modeling of each component and the performance of the cycle are defined by Equations (1) to (10)

$$\dot{W}_{in} = \dot{m}_{wf}(h_2 - h_1) \quad [kW] \qquad (1)$$

$$\dot{Q}_{in} = \dot{m}_{wf}(h_3 - h_2) \quad [kW] \qquad (2)$$

$$\dot{W}_{out} = \dot{m}_{wf}(h_3 - h_4) \quad [kW] \qquad (3)$$

$$\dot{Q}_{out} = \dot{m}_{wf}(h_4 - h_1) \quad [kW] \qquad (4)$$

$$\dot{W}_{net} = \dot{W}_{out} - \dot{W}_{in} \quad [kW] \qquad (5)$$

$$UA = \frac{\dot{Q}}{\Delta T_{lm}} \quad \left[\frac{kW}{K}\right] \qquad (6)$$

$$\Delta T_{lm} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{log\frac{(T_{h,in} - T_{c,out})}{(T_{h,out} - T_{c,in})}} \quad [K, °C] \qquad (7)$$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \times 100\% \quad [\%] \qquad (8)$$

$$\eta_{isen,pump} = \frac{h_2 - h_1}{h_{2s} - h_1} \qquad (9)$$

$$\eta_{isen,tur} = \frac{h_3 - h_4}{h_3 - h_{4s}} \qquad (10)$$

where $\dot{W}$ is the rate of work in the system [kW], $\dot{Q}$ is the rate of heat transfer in the system [kW], h is enthalpy of the working fluid [kJ / kg], $\dot{m}_{wf}$ is flow rate of the active working fluid in the system [kg/s], T Is the temperature $[K, °C]$, UA is the rate that indicates the size of the heat exchanger [kW/K] and C_{min} is the smallest product of $\dot{m}$ and C_p in the heat exchanger [kW/K].

2.5 The working fluid use to simulation

Table 1: Properties of working fluids tested.

Name	$T_{critical}$ (°C)	$P_{critical}$ (MPa)	Name	$T_{critical}$ (°C)	$P_{critical}$ (MPa)
Octane	296.17	2.50	R141b	204.35	4.21
Benzene	288.87	4.91	Pentane	196.55	3.37
Cyclohexane	280.45	4.08	Ipentane	187.20	3.38
Heptane	266.98	2.74	R245ca	174.35	3.94
Cyclopentane	238.57	4.57	RE245fa2	171.63	3.43
Ihexane	224.55	3.04	R245fa	154.00	3.65
R113	214.06	3.39	Isobutane	134.66	3.63

3.1 RESULT AND DISCUSSION

3.1 Validation

Based on the simulation of the ORC cycle, the simulation will be compared with other research, compared with the 1 MW ORC cycle [19]. The ORC system simulation results in the supercritical, subcritical and trilateral models. By comparing with the comparison values Get results as Tables 2, 3 and 4.

Table 2: Validation of supercritical plant

Parameter	[19]	Result value	Error (%)
		Supercritical ORC	
T_4 (K)	401.00	406.76	1.44
T_6 (K)	394.29	398.22	1.00
T_8 (K)	348.94	348.65	0.08
η_{th}	18.63	18.96	1.77

Table 3: Validation of subcritical plant

Parameter	[19]	Result value	Error (%)
		Subcritical ORC	
T_4 (K)	396.41	396.03	0.10
T_6 (K)	408.70	407.12	0.39
T_8 (K)	348.35	349.03	0.05
η_{th}	17.27	17.06	1.22

Table 4: Validation of trilateral plant

Parameter	[19]	Result value	Error (%)
		Trilateral ORC	
T_4 (K)	358.15	358.15	0.00
T_6 (K)	370.53	370.47	0.02
T_8 (K)	348.15	348.15	0.00
η_{th}	19.79	19.79	0.01

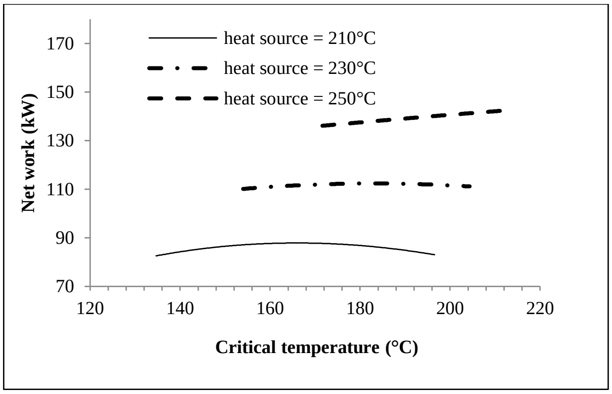
From Tables 2, 3 and 4, it was found that. Validation result of supercritical ORC has the highest error of 1.77%, the lowest of 0.08%. In the subcritical ORC. The highest error is 1.22%, the lowest at 0.05% and the trilateral ORC has the highest error of 0.02, the lowest at 0.00%.

3.2 Results

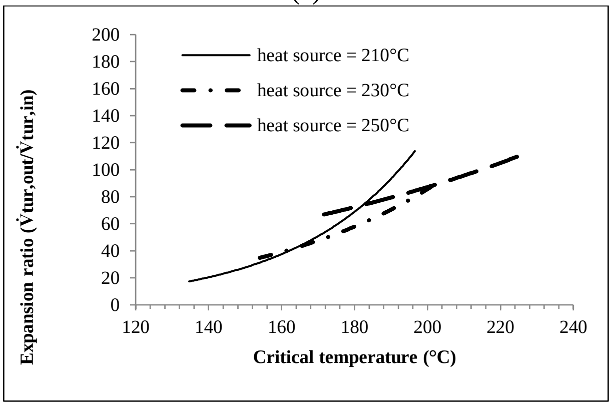
The design is designed to bring the heat source at 210°C, 230°C and 250°C to be used in the production of energy by determining the pinch point temperature value in each thermal equipment equal 10°C and the temperature of coolant increased by 10°C after being heated. By specifying that the heat source is water, the pressure is 10.00 MPa and the flow rate is 1.00 kg/s and working fluid is on Table 1.

3.2.1 Supercritical ORC

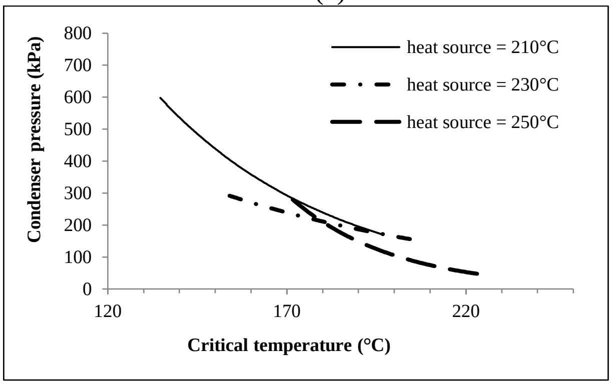
Simulation results of the supercritical ORC plant are shown in Fig. 4.



(a)



(b)



(c)

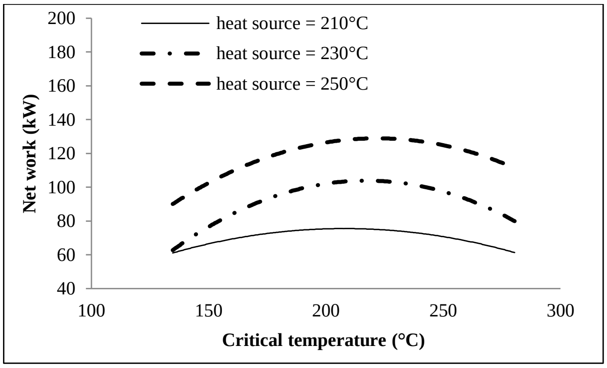
Fig. 4. (a) Net power, (b) expansion ratio and (c) condenser pressure versus the working fluid's critical temperature for the supercritical ORC plant

Based on the simulation with working fluid at Table 1 results, the working fluid in this range of this heat source temperature in supercritical ORC should be R245fa, R245ca and R141b because it is found that the simulation of supercritical ORC cases. Can be found that the working temperature with a critical temperature should below than heat source 40°C to 50°C. Those working can provide the highest net power in the heat source temperature range between 210°C to 250°C and when compared with the research of [16], they are similar trend to each other in the range of 30°C to 50°CE as shown in Fig. 4(a).

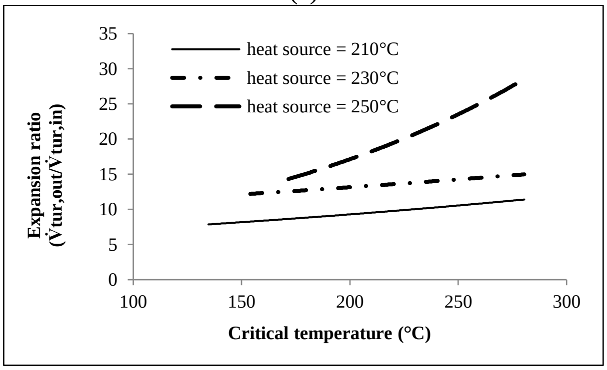
Consider the expansion ration as shown in Fig. 4(b), when using a working fluid that has a higher critical temperature, the expansion ratio from the expander will increase as well. When the size of the expander be large as well, and when considering the pressure that the condenser is from Fig. 4(c), found that we should not use a working fluid that causes the temperature to cause the condenser to decrease below atmospheric pressure because it may be possible to air is leaking into system.

3.2.2 Subcritical ORC

Simulation results of the subcritical ORC plant are shown in Fig. 5.



(a)



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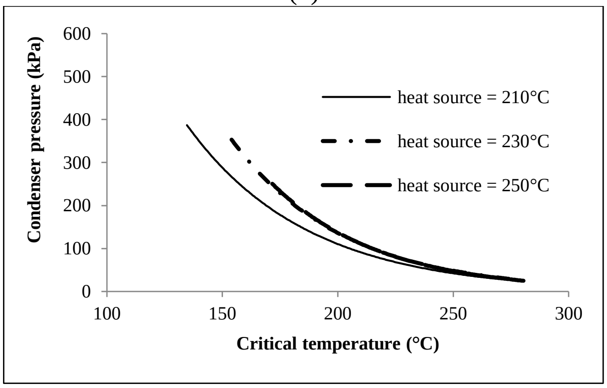


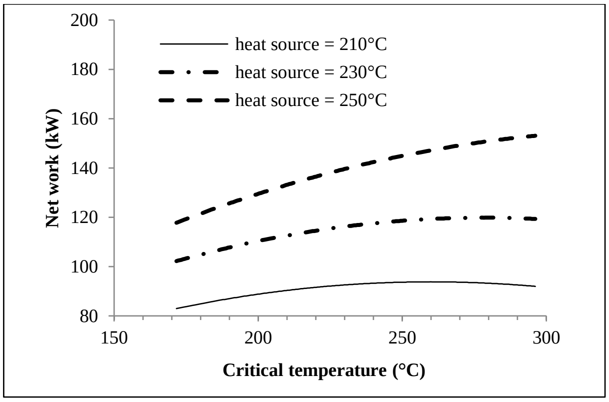
(c)

Fig. 5. (a) Net power, (b) expansion ratio and (c) condenser pressure versus the working fluid's critical temperature for the subcritical ORC plant

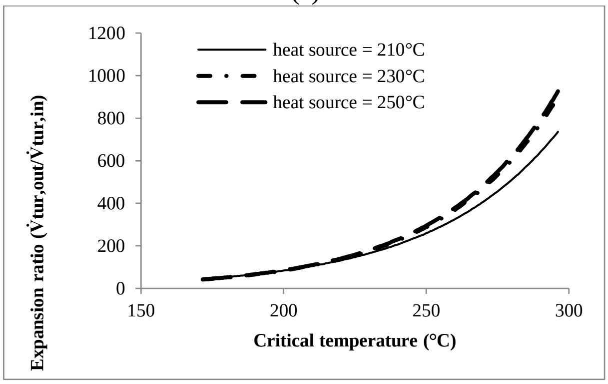
The simulation results of subcritical ORC cycle from net power tendency to working fluid critical temperature, it can be found that the selection of working fluid by giving the critical temperature below than heat source 40°C and 60°C will get the highest net power. And considering the expansion and pressure of the condenser will have the same tendency to simulate supercritical ORC. So, for that reason the working fluid in this case should be RE245fa, R245fa and pentane.

3.2.3 Trilateral plant

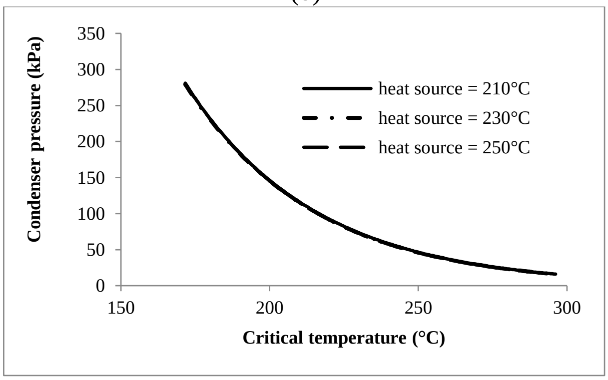
Simulation results for the trilateral plant are shown in Fig. 6.



(a)



(b)



(c)

Fig. 6. (a) Net power, (b) expansion ratio and (c) condenser pressure versus the working fluid's critical temperature for the supercritical trilateral plant

As a result of the simulation of the ORC cycle model, the high critical temperature working, will generate also high net power, as shown in Fig. 6(a). Of result of expansion ratio and condenser pressure has the same tendency as the simulation of the ORC model supercritical and subcritical flow Fig. 6(b) and 6(c).

Choose to working fluid by using the critical temperature of the working fluid by considering the rate of expansion ratio of the expander not too high because expander also huge. And, the pressure at the condenser not less than that of the atmosphere. Between 180°C to 210°C for heat sources at 210°C - 250°C. So, the working fluid should be Isopentane, Pentane and R141b.

Simulating the comparison using water as a working fluid because water is generally use in power generation, it was found that the use of water as a working fluid would cause the expansion rate in the expander to be very high due to the high temperature when compared with the refrigerant working fluid, which is equal to 373°C Based on Fig. 6(b), it can be seen that the growth rate is high when the critical temperature of the working fluid is high.

3.2.4 Optimal simulations at the heat source temperature of 210°C - 250°C

As a result of the simulation of the ORC cycle supercritical, subcritical, and trilateral when determining the appropriate functional working fluid as shown in Table 5.

Table 5: Optimal results for the heat source temperature at 210°C - 250°C

Type	T_{hs} (K)	Working fluid	$T_{critical}$ (K)	P_{cond} (kPa)	P_{evap} (kPa)
	483.15	R245fa	154.00	333.43	5772.06
Super.	503.15	R245ca	174.35	230.18	7188.47
	523.15	R141b	204.35	180.90	5699.10
	483.15	RE245fa2	171.63	195.04	2177.56
Sub.	503.15	R245ca	174.35	229.49	2896.32
	523.15	Pentane	196.55	146.85	2806.59
	483.15	Isopentane	187.20	201.06	3199.88
TLC.	503.15	Pentane	196.55	154.92	3155.73
	523.15	R141b	204.35	181.15	3875.39

The result of the simulation when taking the appropriate working fluid by considering the maximum net power as in Table 5, when comparing the results of the net power obtained in each heat source temperature, UA and the rate of expansion of the work in the expander can be achieved as shown in Figs. 7, 8, 9 and 10.

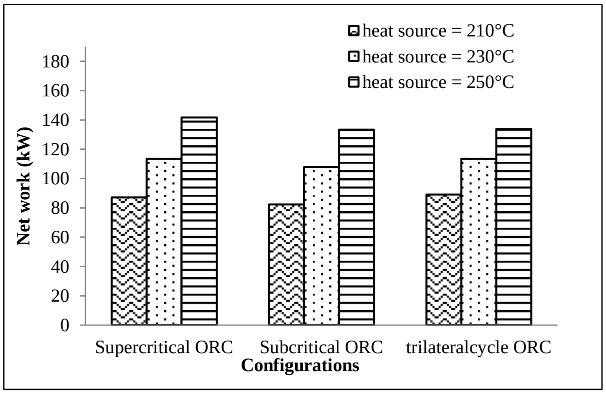


Fig. 7. Maximum net power at each heat source temperature

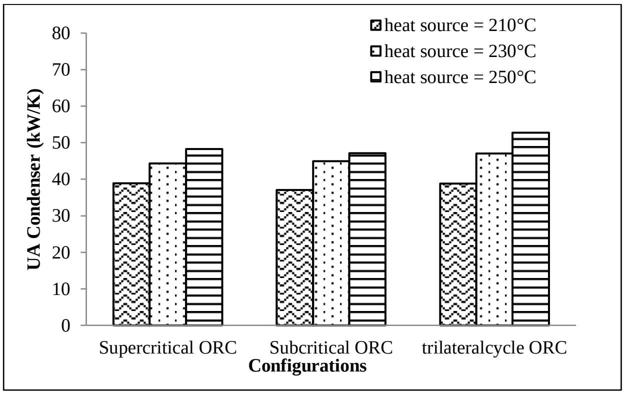


Fig. 8. $UA_{condeser}$ at each heat source temperature

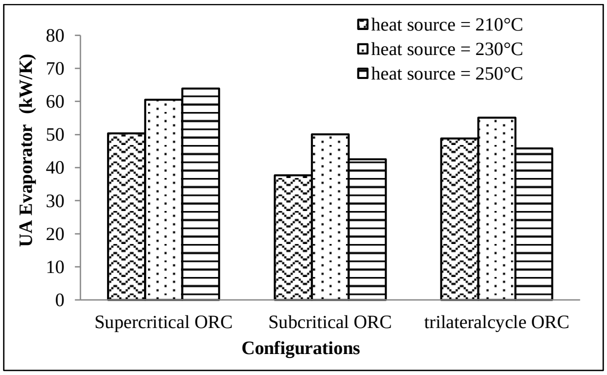


Fig. 9. $UA_{evaporatior}$ at each heat source temperature

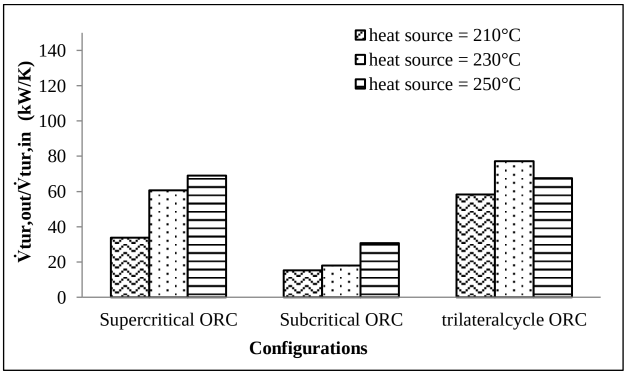


Fig. 10. Expantion ratio at each heat source temperature

Based on the simulation results, the simulation of the ORC cycle model supercritical get the highest net power compared to the same temperature range as Fig. 7. The net power output is 141.72 kW. R141b is working fluid at the heat source temperature is 250°C in cycle.

When considering the appropriate working fluid of the heat source temperature in the range of 210°C to 250°C was found that the size of the heat exchanger evaporator (UA) of supercritical will have largest size and the next will be trilateral and subcritical respectively due to supercritical ORC need to increase temperature of working fluid to critical temperature point of working fluid. That why supercritical need large evaporator (high UA value) when compare with subcritical ORC and trilateral Rankine cycle. As for the size of the heat exchanger (UA), it is found that in the highest simulation, it is the trilateral. And supercritical and subcritical sequences, as shown in Fig. 8 and 9, where the size of UA depends on the type of working fluid.

From the simulation as shown in Fig. 10, the rate of expansion of the working fluid can be considered as the simulation trilateral Rankine cycle has highest expansion, because expander will expand working fluid form liquid point to mixture point. It extremely differences of specific volume. When compare with supercritical and subcritical ORC.

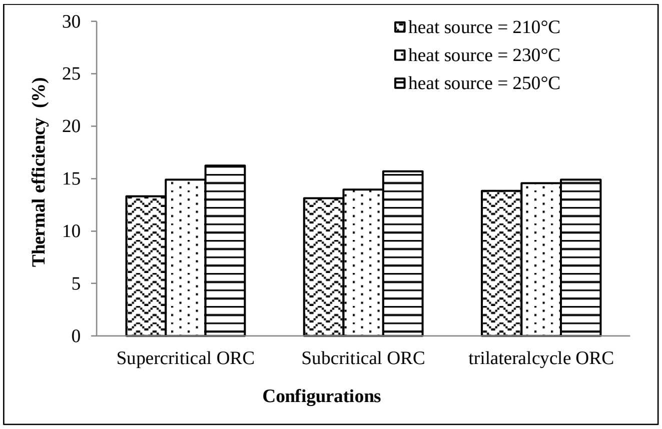


Fig. 11. Thermal efficiency at each heat source temperature

Figure 11 shows that the higher the temperature of the heat source, the higher the efficiency. And from the simulation results found that the simulation of the ORC cycle is supercritical will achieve the highest thermal efficiency at 16.25%.

So, for all those reasons. In heat source temperature 210°C - 250°C should use supercritical ORC and use R141b be working fluid.

3.3 Off-design results

Off-design simulation is needed to know when condition of system has change. This off-design simulation will be considering the temperature of heat source and cooling water change follow Table 6 how that affect to net power output of cycle.

Table 6: Cases for off-design simulations

Case	$T_{heat\ source}$	$T_{cooling\ water}$
1		T_{cf} - 3
2	T_{hs} - 5	T_{cf}
3		T_{cf} + 3
4		T_{cf} - 3
5	T_{hs}	T_{cf}
6		T_{cf} + 3
7		T_{cf} - 3
8	T_{hs} + 5	T_{cf}
9		T_{cf} + 3

When considering the heat source at 250°C, it was found that when the temperature of the heat source and the heat source temperature was changed by the simulation results, the net was considered as Table 7.

Table 7: Results of off-design simulations

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
					$\dot{W}_{net}$ (kW)				
Supercritical	141.68	136.33	131.95	148.86	141.72	139.81	156.67	152.04	147.08
Subcritical	132.00	127.65	123.46	135.93	133.40	128.02	143.37	136.40	132.33
Trilateral	132.62	128.01	123.60	139.07	133.80	128.85	144.69	139.78	135.29

The simulation results, as shown in Table 2, indicate that Cases 1, 2, 3 and 6 of the trilateral simulation of the ORC model work with 4.2 kg/s and supercritical flow. The flow rate of the work with 3.6 kg/s will make the net power lower than the design value (Case 5), but the subcritical simulation at the flow rate works with 1.6 kg/s. There are 9 cases as well. Can give the net power equal to the designed value when the heat of the heat source decreases and the temperature of the heat source increases, the net power also decreases.

If we want to reduce the net power, you can return the net power as by adjusting the flow rate of the working fluid in order to increase the net power value in the case that the net network cannot be created as much as the designed value with results as shown in Tables 8, 9 and 10.

Table 8: Net power versus flow rate of the working fluid for the supercritical plant

Case	$\dot{W}_{net}$ **(kW)**	$\dot{m}_{wf}$ **(kg/s)**	$\dot{W}_{net,increase}$ **(kW)**
1	133.85	4.09	1.23
2	133.84	3.49	5.82
3	130.24	3.27	6.65
6	133.84	3.81	4.98

Table 9: Net power versus flow rate of the working fluid for the subcritical plant

Case	$\dot{W}_{net}$ (kW)	$\dot{m}_{wf}$ (kg/s)	$\dot{W}_{net,increase}$ (kW)
1	133.03	1.54	1.03
2	129.50	1.61	1.85
3	125.32	1.68	1.86
6	129.38	1.76	1.36
9	133.65	1.98	1.32

Table 10: Net power versus flow rate of the working fluid for the trilateral plant

Case	$\dot{W}_{net}$ **(kW)**	$\dot{m}_{wf}$ **(kg/s)**	$\dot{W}_{net,incress}$ **(kW)**
1	133.85	4.09	1.23
2	133.84	3.49	5.82
3	130.24	3.27	6.65
6	133.84	3.81	4.98

Based on the simulation results, adjusting the flow rate of the working fluid, as shown in Tables 8, 9 and 10 found that the flow rate adjustment of the working fluid can increase net power. Because when decrease flow rate can give more time working fluid flow in evaporator. That make enthalpy out of evaporator also increase. It can be increase new power output follow eq.4. But it not enough to make the net power equal to the designed value. May have to make other adjustments that affect the net power value.

4. Conclusions

The performance of a subcritical ORC, supercritical ORC, and trilateral RC with the heat source temperatures of 210°C - 250°C were analyzed. Several working fluids for each plant were examined. It was found that the supercritical plant with a working fluid that its critical temperature is 40°C to 50°C below the heat source temperature provides the highest net power output. When the heat source temperature is 250°C, the supercritical plant with R141b as its working fluid provides the net power output of 141.72 kW and thermal efficiency of 16.25%. In the off-design simulations, it was found that a proper adjustment of the working fluid flow rate can maintain the net power output.

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