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Study of Development Scenarios for Bottoming Unit Binary Cycle to Utilize Exhaust Steam from Back Pressure Turbine Geothermal Power Plant

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Abstract. Binary cycle using organic working fluid or ORC system has been applied in geothermal and some other industrial processes to recover low grade and waste energy to generate electricity. The conventional system to utilize geothermal energy is a condensing system or back pressure system which depend on a turbine used in the system. Two units of the power plant in Flores, Indonesia are using back pressure turbine, which means that there is still a chance to increase the electrical power of the steam which is released through the turbine. The amount of exhaust steam available from these two units power plant is more than 62,000 kg per hour with 99°C of temperature and around 2,430 kJ/kg enthalpy. This research is trying to get the optimum power that can be generated by the ORC regarding other consideration parameters such as ambient temperature, thermodynamics condition of resource steam, and energy conversion of each apparatus. It is the aim of this paper to present a thermodynamic study on the utilization of ORC as the bottoming cycle with various types of working fluids to produce additional electricity. Several working fluids are chosen to find the optimum ORC system to utilize this exhaust steam such as isobutane, butane, isobutene, isopentane, propane, propyne, neopentane, R245fa, R236fa, and R134a. ORC system used in this research is simple ORC with basic components such as Pre-Heater, Evaporator, Expander, Condenser, and Pump. The properties of working fluids are calculated by REFPROP. The results show that this binary cycle can generate up to 2.25 MW with the thermal efficiency around 10% depend on the working fluid used. Two working fluids in this scenario that provide the best power generated are Propyne and Isopentane. The type of working fluid must also be considered, propyne is a wet type while isopentane is a dry type working fluid.

1. Introduction

Steam turbines are divided into two types based on the process that occurs after the turbine. These two turbine types are condensing turbine and back pressure turbine. Figure 1 shows the difference between condensing and back pressure turbine. Condensing turbine is connected to the condenser so that the steam on the turbine outlet side goes directly into the condenser and the phase turns into a liquid phase. The phase change also means a change in density, and it forced the pressure to drop, so that the pressure on the condenser will be close to vacuum. Meanwhile, the back pressure turbine is not connected to a condenser but is directly flowed into atmospheric air. So that the pressure value on the output side of the turbine must be greater than the atmospheric pressure around the location of the turbine. Back pressure turbine has less pressure drop in the process, which means for the same operating load, back pressure turbine needs more steam than condensing turbine type. However, if we look from the financial side, the back pressure turbine has less capital and operational cost because condensing turbine needs a more auxiliary system such as an ejector, condenser, extraction pump, etc. The back pressure turbine has less moisture at the outlet side which reduce erosions and increase efficiency [1]. Exhaust steam from back pressure turbine still has a considerable amount of energy to be utilized. Binary cycle or ORC is a suitable technology to utilize low grade and waste energy (as from an exhaust steam of a back pressure turbine) for generating electricity [1] [2] [3] [4]. A binary power plant in Sarulla [1] and Svartsengi [2] are using the exhaust steam from the main plant as the heat source of their binary power plant. At the Svartsengi plant 4, the heat source of this unit comes from low-pressure exhaust steam of plant 3 back pressure turbine with 38.5 kg/s at 1.2 bar. At the Sarulla plant, the binary cycle bottoming units were placed at the outlet side of the turbine, so they can use the exhaust steam as the heating fluid for the binary cycle. Two units of the power plant in Flores, Indonesia are also using back pressure turbine which is still likely to be used to generate additional electricity for the existing system.

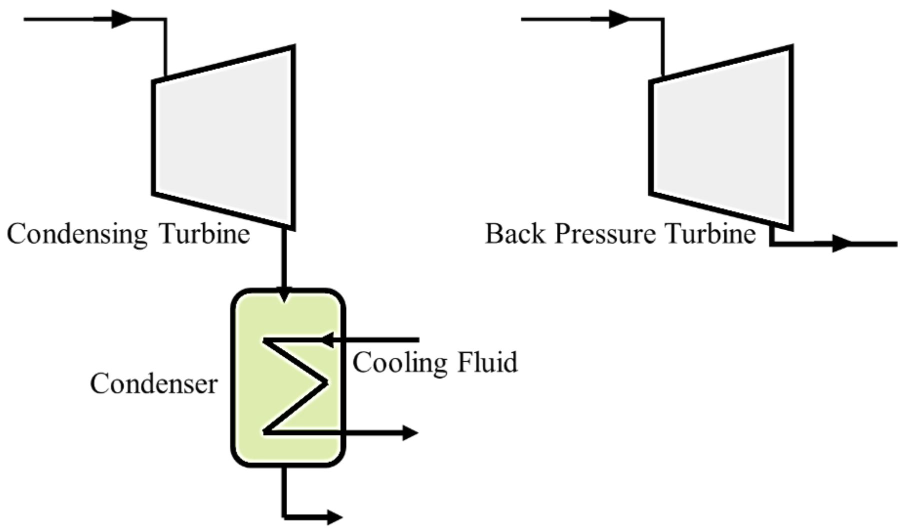

Figure 1. Comparison between Condensing (left) and Back pressure turbine (right).

The Organic Rankine Cycle (ORC) is a binary cycle that can be used as a bottoming cycle of the geothermal energy conversion system to optimize the electricity produced. ORC has been applied in geothermal and some other industrial processes to recover low grade and waste energy such as an exhaust steam from the back pressure turbine to generate additional electricity. ORC binary power plants are utilized for medium and low-temperature sources, and as a bottoming cycle for the steam turbine [5] [6]. With the inclusion of a binary cycle in the geothermal system, the total energy efficiency increases [2]. It is the aim of this paper to present a thermodynamic study on the utilization of ORC as the bottoming cycle of the back pressure turbine with various types of working fluids to produce additional electricity.

2. Binary Cycle Power Plant

Binary cycle power plant consists of two cycles of working fluid and heating fluid. In geothermal, the heating fluids can be either brine or steam. The working fluids are chosen by the thermodynamic

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properties such as critical temperature which has to be lower than water and vapor pressure, which has to be greater than water. Safety, health and environmental impact issues should also be considered [7].

Organic Rankine cycle (ORC) is a binary cycle that uses an organic fluid as a working fluid. The advantage of using an organic fluid is its lower boiling point than water, which leads to easier fluid evaporation by heat from a low-temperature heat source. Therefore, ORC has the ability to utilize a relatively low-temperature heat source [4]. If the geofluid temperature is 150°C or less, it becomes difficult, although not impossible, to build a flash-steam plant that can efficiently and economically [8]. As the conventional flash steam plants are not efficient in technical and economical aspect to utilize geothermal resource below 150°C, the binary cycle or specifically ORC is a perfect choice. There are several advantages in using an ORC to recover low-temperature geothermal resources, including economical utilization of energy resources, smaller systems and reduced emissions of CO, CO_2, NO_x and other atmospheric pollutants [3]. Electricity can now be generated from the resource with the temperature down to 100°C using an ORC process [9]. ORC is a system uses an organic substance as a working fluid in order to utilize low-grade heat sources and consists of an evaporator (heating area), a turbine and a condenser (cooling area) [10]. The ORC operation principle is similar to as the conventional Rankine cycle, but in this case, the working fluid is an organic compound of a low boiling point instead of water, thus decreasing the temperature needed for evaporation [11].

2.1. Thermodynamic Cycle

As been stated by [8], the thermodynamic cycle of the binary power plant is very close to a conventional fossil power plant. The working fluid receives heat from heating fluid for an evaporating process, expands through an expander, condenses, and was returned to the evaporator. The thermodynamic cycle in a binary power plant is a closed cycle. The schematic diagram in Figure 2 shows the main components of the binary cycle.

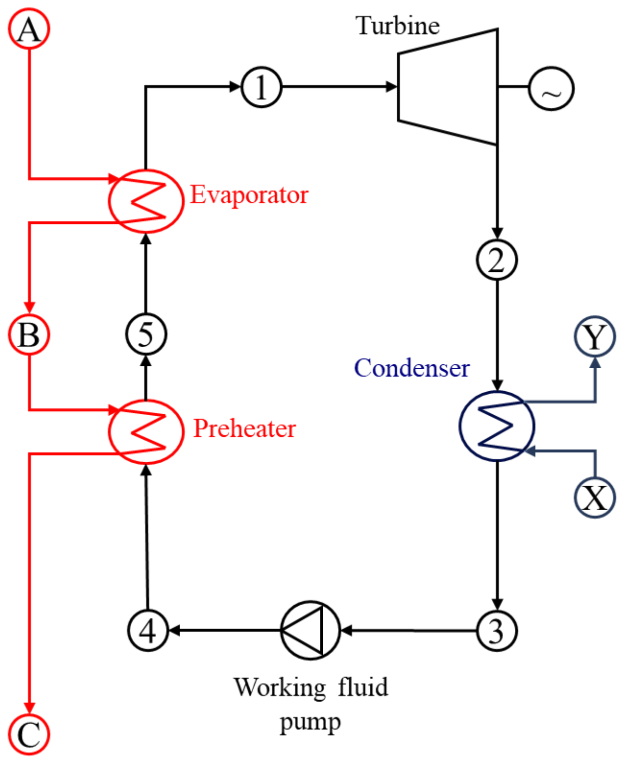

Figure 2. Schematic diagram of binary cycle [2].

The thermodynamic process that occurs in the binary cycle is similar to Rankine cycle where saturated vapor will form on the evaporator, then it will return to the liquid phase after condensation in the condenser [2]. Figure 3 illustrates a closed cycle of working fluid from a binary cycle using a dry-type working fluid. Each color in this T-s diagram has meaning. The red color means that it was a heating process in pre-heater and evaporator. In this step, the working fluid has received the heat from heating fluid or in this case from the exhaust steam. The green color means the isentropic process in the turbine or expander. The blue color represents the condensing process or the heat rejection process in the condenser.

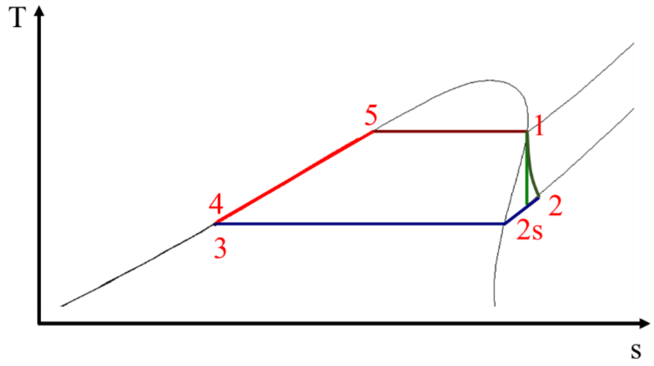

Figure 3. T-s Diagram for binary cycle using dry-type working fluid.

The binary cycle in Figure 3 consist of 4 main processes,

- Line 4-5-1 shows isobaric heat transfer process from heating fluid to the working fluid. This process occurs in the pre-heater and evaporator.
- From 1 to 2 is the isentropic expansion process in the turbine or expander.
- Line 2-3 is the heat release process and condensation in the condenser at constant pressure.
- Line 3-4 is the pumping process of working fluid in order to increase its pressure to evaporating pressure that ideally is the isentropic process

2.1.1. Turbine. The binary cycle turbine converts working fluid enthalpy into the kinetic energy in the form of turbine shaft rotation. The turbine is coupled to the generator to generate electricity. Thermodynamic analysis of the binary cycle turbine is similar to a steam turbine. The assumption used is neglecting potential and kinetic energy, adiabatic and steady. The equation of the process in a turbine can be expressed as follows:

$$\dot{W}_T = \dot{m}_{wf}(h_1 - h_2) = \dot{m}_{wf}\eta_T(h_1 - h_{2s}) \quad (1)$$

The turbine efficiency (η_T) is given by the manufacturer and it represents the ratio between the real enthalpy change through the turbine to the largest possible (isentropic) enthalpy change [12].

2.1.2. Condenser. The condenser is a heat exchanger that exchanges heat in a working fluid vapor into a cooling fluid cycle. The cooling fluid used can be water or air. This heat exchange condition is maintained under a constant pressure condition (isobaric condition). When the working fluid used is the dry type, the condition when exiting the turbine is a superheated condition. Then, in the condenser, there will be two steps process, as seen in Figure 4. The first process step is to de-superheat to saturated vapor, and then the second step is the condensation process while releasing heat to the cooling fluid.

The heat transfer between the working fluid and the cooling fluid in the condenser can be expressed as follow:

$$Q_{2-3}\dot{} = m_{wf}(h_2 - h_3) = \dot{m}_{cf}C_{cf}(T_x - T_y) \tag{2}$$

where T_x and T_y are the cooling fluid temperature at X and Y in Figure 2.

2.1.3. Pump. The working fluid pressure dropped in the turbine due to the expanding effect. At the pump, the pressure of the working fluid is returned to the evaporation pressure. The power to be transferred to working fluid from the pump can be expressed as follow

$$\dot{W}_P = \dot{m}_{wf}(h_4 - h_3) = \frac{\dot{m}_{wf}(h_{4s} - h_3)}{\eta_P} \tag{3}$$

2.1.4. Preheater and Evaporator. These components are heat exchanger where the heating fluid, either it was brine or exhaust steam in this case, transfers its energy to the binary cycle working fluid. As we can see from Figure 4 about heat transfer diagram, the 4-5-1 process is the heat transfer process from heating fluid to working fluid. The working fluid must be heated from its inlet temperature (4) to its outlet temperature (1). The minimum temperature difference in the heat exchanger between the heating fluid and the working fluid is called pinch-point (T_{pp}).

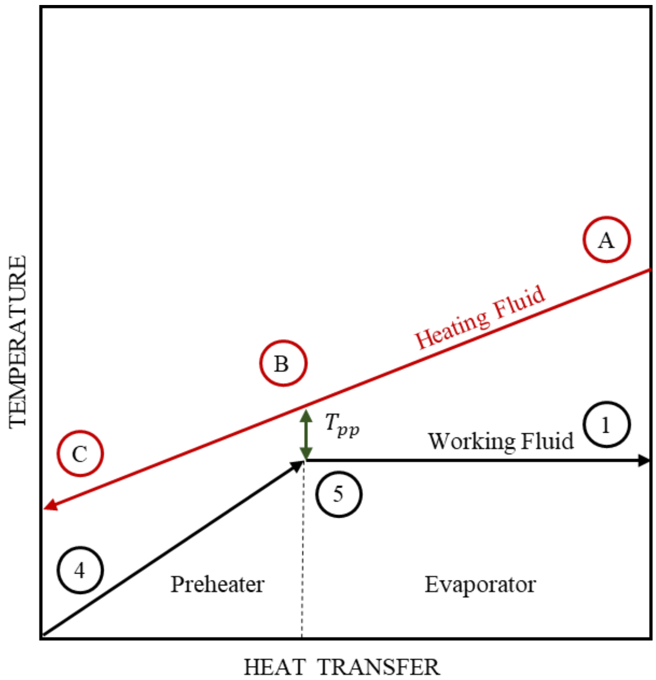

Figure 4. Temperature - Heat transfer diagram for preheater and evaporator [8].

Thus, the two heat exchangers may be analyzed separately as follows:
Pre-heater:

$$\dot{m}_{hf}C_{hf}(T_B - T_C) = \dot{m}_{wf}(h_5 - h_4) \tag{4}$$

Evaporator:

$$\dot{m}_{hf}C_{hf}(T_A - T_B) = \dot{m}_{wf}(h_1 - h_5) \tag{5}$$

2.2. *Working Fluid Selection*

The thermodynamic conditions and temperature of the heat source vary widely and hundreds of substances can be used as a working fluid in that condition. Selection of working fluid for ORC is critical. The working fluid influences significantly to cycle efficiency, component sizing, expander design, economic viability, safety, and environmental impact.

Table 1 shows some working fluids candidates for the binary cycle used in this study. The selection of working fluids based on a critical point of temperature and pressure. Because the heat source in this study is 99°C of temperature, so the working fluids candidates must have a lower boiling point and the critical temperature is not so far from the heat source temperature. In addition to temperature consideration, according to Aljundi, the working fluids must also consider other characteristics such as Global Warming Potential (GWP), and Ozone Depletion Potential (ODP) [7]. Table 2 shows the value of ODP and GWP from selected working fluids. As shown in Table 2, R134a, R245fa, and R236fa have a high GWP value that means those working fluids have a high risk to stimulate global warming.

Table 1. Working fluids used in this binary cycle [8] [13] [14].

Working Fluid	SHRAE number	Formula	$T_{boiling}$ (°C)	Tc (°C)
Propane	R-290	C_3H_8	-42	96.95
Propyne		CH_3CCH	-23.2	129
Isobutane	R-600a	i-C_4H_{10}	-11.7	134.6
Isobutene		C_4H_8	-6.9	144
Butane	R-600	C_4H_{10}	-0.4	150.8
Isopentane	R-601a	i-C_5H_{12}	27.7	187.8
Neopentane		C_5H_{12}	9.5	160.6
1,1,1,2-Tetrafluoroethan	R-134a	$C_2H_2F_4$	-26.3	101
1,1,1,3,3-Pentafluoropropan	R-245fa	$C_3H_3F_5$	15.3	153
1,1,1,3,3,3-Hexafluoropropan	R-236fa	$C_3H_2F_6$	-1.4	124

Table 2. ODP and GWP value for the selected working fluids [15].

Working Fluid	ODP	GWP
Isobutane	0	3
Butane	0	4
Isopentane	0	5
Isobutene	0	3
Propane	0	3
R-134a	0	1430
R-245fa	0	1030
R-236fa	0	9810

These working fluids are divided into wet, isentropic, and dry types. Figure 5a-c [2] shows the T-s diagram of wet, isentropic, and dry type working fluids. In wet-type working fluids, the fluid on the outlet side of the turbine will fall to the inside of the saturation dome, and it can be harmful for the turbine blades and can lessen the cycle efficiencies. While for the isentropic and dry type working fluid, the fluid exits from the turbine will be at saturation or superheated vapor conditions.

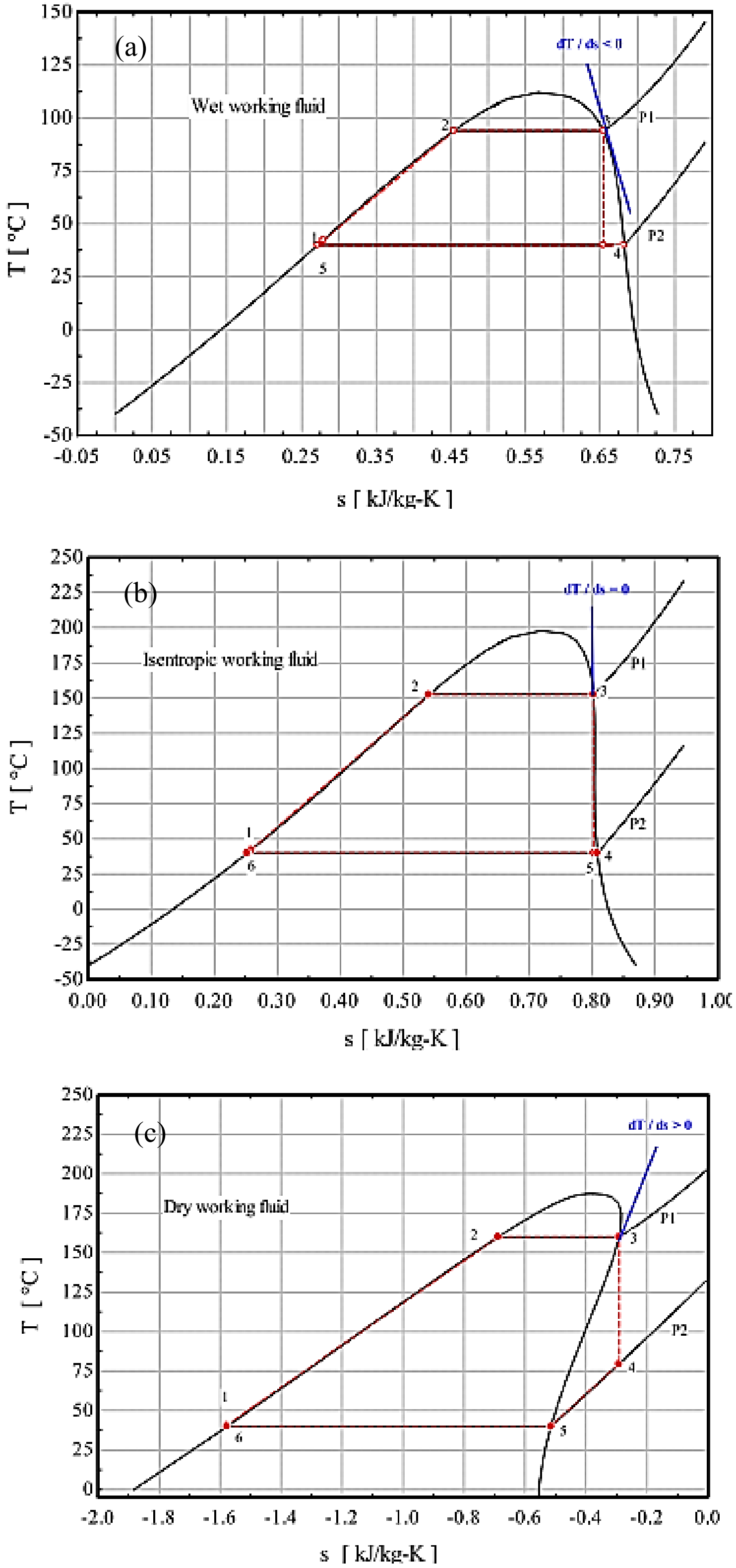

Figure 5. (a) T-s diagram for wet working fluids; (b) T-s diagram for isentropic working fluids; (c) T-s diagrams for dry working fluids [2].

3. Conceptual Design of Bottoming Binary Cycle

As mentioned before that the exhaust steam from a back pressure turbine still can be utilized by bottoming unit binary cycle to produce additional electricity. A power plant in Flores, Indonesia has two units of back pressure turbine which operate at steam inlet pressure equal to 10 bar and the outlet side is at 0.98 bar. Both back pressure turbine produced 31.2 ton exhausted steam per hour for each turbine with the average temperature is 99°C. Variable temperature, pressure, and mass flow of state A are given by the data of exhaust steam from the plant. The pinch point of the heat exchanger is optimized at 5°C [16] [17], and the mass flow rate of the working fluids are set 45 kg/s.

The exhaust steam will be connected to a binary cycle as heating fluid. The model made in this study of the binary cycle is shown in Figure 6. The black line is the closed cycle of the working fluid and the red line is heating fluid, while the blue line is the cooling fluid. REFPROP 9.0 is used to make the thermodynamic calculations of this whole cycle. Several assumptions are used in this study as shown in Table 3. The optimum turbine input pressure value can be obtained by using the pinch point parameter. The value of ambient temperature is 27.45°C which is being used as the limit of the condenser parameters. Air Cooled Condenser (ACC) is used as the cooler of the working fluid cycle in this ORC model. The required air flow in ACC is calculated by considering the temperature changes needed to change the working fluid phase in the condenser, from the vapor phase or the mixed-phase from the turbine output side to the liquid phase. The parasitic load produced by the fan of ACC is calculated based on the required air flow with the assumption in Table 3.

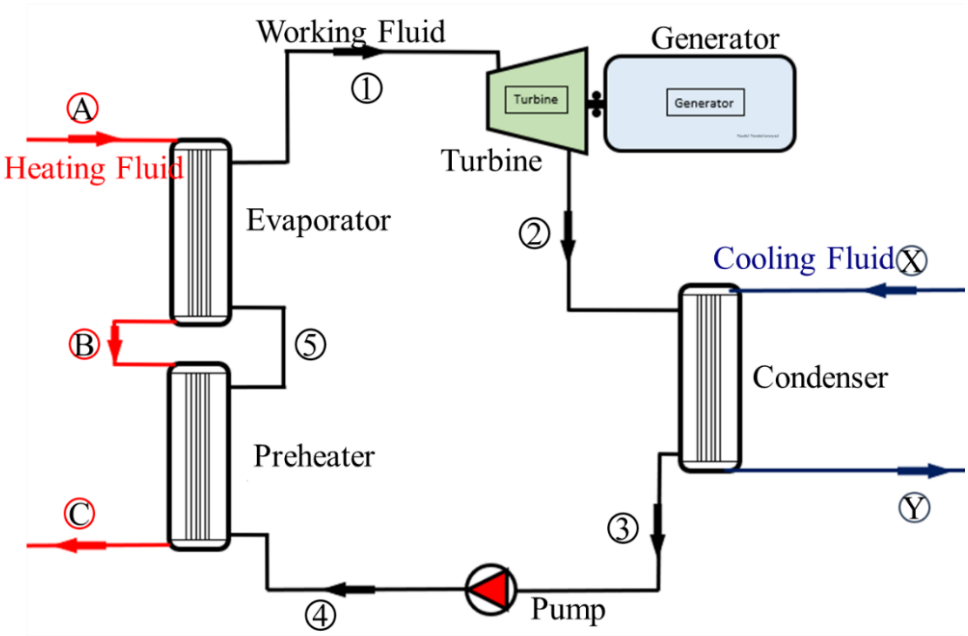

Figure 6. Schematic diagram of the binary cycle design used in this study.

Table 3. Assumptions used in this study.

Parameters	**Value**	**Source**
η turbine	90 %	[16] [17]
η generator	96%	[16]
η pump	80%	[16]
Air Cooled Condenser Fan Power	0,15 kW/kg/s of air	[18]
Pinch Point	5°C	[16] [17]

4. Results and Discussion

4.1. Result

After the thermodynamic calculations of this ORC model, we will get the net power that can be produced by the ORC and also the thermal efficiency values of each working fluid used in the ORC models. The example of thermodynamic calculation in the ORC model with selected working fluid is shown in Table 4. The example in Table 4 is using Isopentane as the working fluids. Isopentane is a dry working fluid, and that means the outlet side of the turbine (number 2 in this ORC model) is at a superheated vapor phase of the working fluids. It is quite interesting to note here because the heating fluid used is in the vapor phase, so when the heat energy is used to heat and evaporate the working fluid from the liquid phase to the vapor phase, the heating fluid does not decrease in temperature, but only changes the phase to liquid phase. Figure 7 shows the T-s diagram of the thermodynamic process in this study. As shown in Figure 7, the red line (the heating fluid) did not change its temperature.

Table 4. Thermodynamic condition of each state for binary cycle shown in Figure 6 using isobutane as working fluid.

	Unit	**State**							
		A	**B**	**C**	**1**	**2**	**3**	**4**	**5**
T	(°C)	99	99	99	94	58.87	37.45	37.73	94
P	(bar)	0.98	0.98	0.98	6.34	1.39	1.39	6.34	6.34
X	-	0.92	0.56	0.4	1	#Superheated vapor	0	#Subcooled liquid	0
h	(kJ/kg)	2435	1696	1326	446.4	396.8	22.3	23.33	164.6
S	(kJ/kg.K)	6.72	4.74	3.74	1.26	1.27	0.072	0.073	0.490

Working fluids used in this study are isobutane, butane, isopentane, isobutene, propane, propyne, neopentane, R-134a, R-245fa, and R-236fa. Those working fluids are chosen based on the working temperature range of the heating fluid. As shown in Table 5, each working fluid has different optimal working pressure, which implies a different change in enthalpy value. The W_{net} for each working fluid was calculated by subtracting the gross power generated by the generator to required power for the pump and fan. The fan power for air-cooled condenser was assumed 0.15 kW per kg/s of airflow [19], and the air flow was calculated to depend on condenser condition for each working fluids.

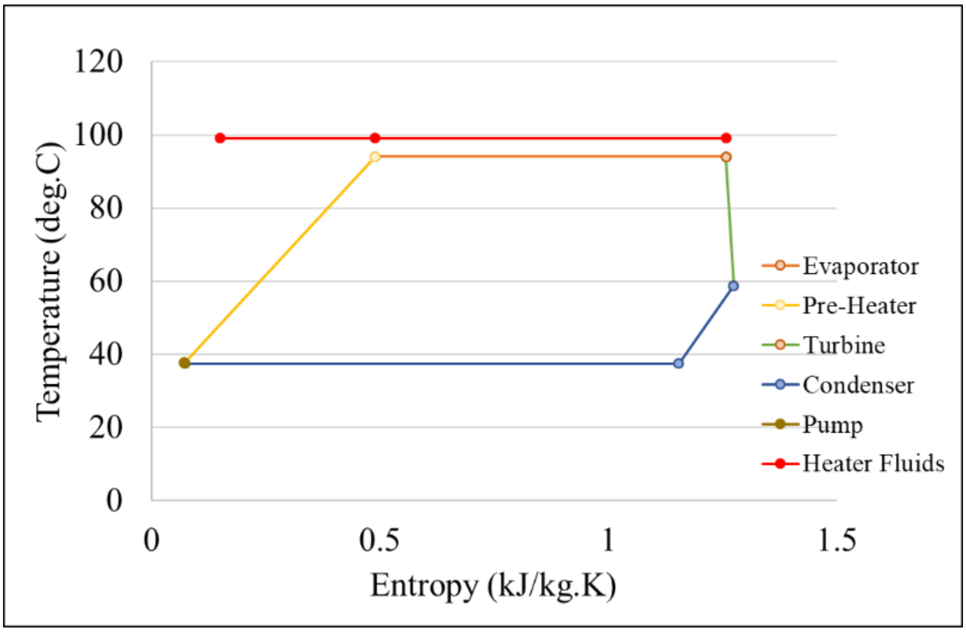

Figure 7. T-s diagram of isopentane working fluid

Table 5. Important parameters of the binary cycle for each working fluid used.

Working Fluids	Pin (bar)	Pout (bar)	Qinput (kJ/s)	Wnett (MW)	Thermal Efficiency
Isobutane	17.75	4.96	17224	1.72	**10.00%**
Butane	13.56	3.52	19172	1.98	**10.31%**
Isopentane	6.34	1.40	19230	2.00	**10.40%**
Isobutene	16.31	4.37	18471	1.90	**10.31%**
Propane	40.49	12.90	13409	1.15	**8.55%**
Propyne	29.80	8.23	21444	2.25	**10.49%**
Neopentane	9.93	2.51	17116	1.71	**9.98%**
R134a	35.2	9.5	7567	0.68	**9.05%**
R245fa	11.05	2.3	10034	1.03	**10.31%**
R236fa	17.08	4.1	7656	0.74	**9.61%**

Each working fluid is calculated using the same steps and then compared the value of thermal efficiency and the net power that can be generated. Figure 8 and Figure 9 shows the comparison of net power generated and thermal efficiency for each working fluid.

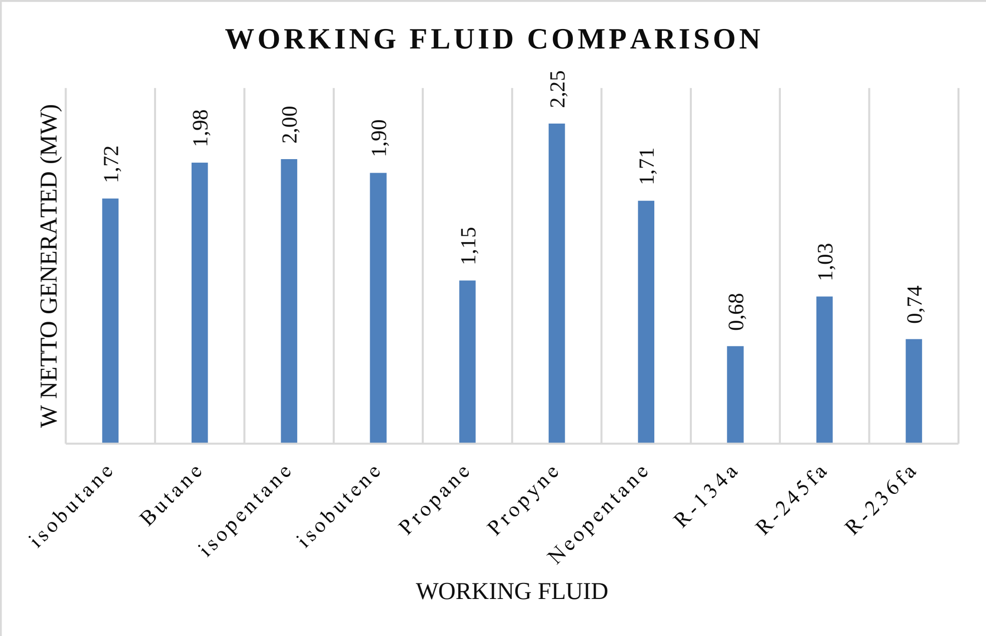

Figure 8. Working fluids comparison by power generated.

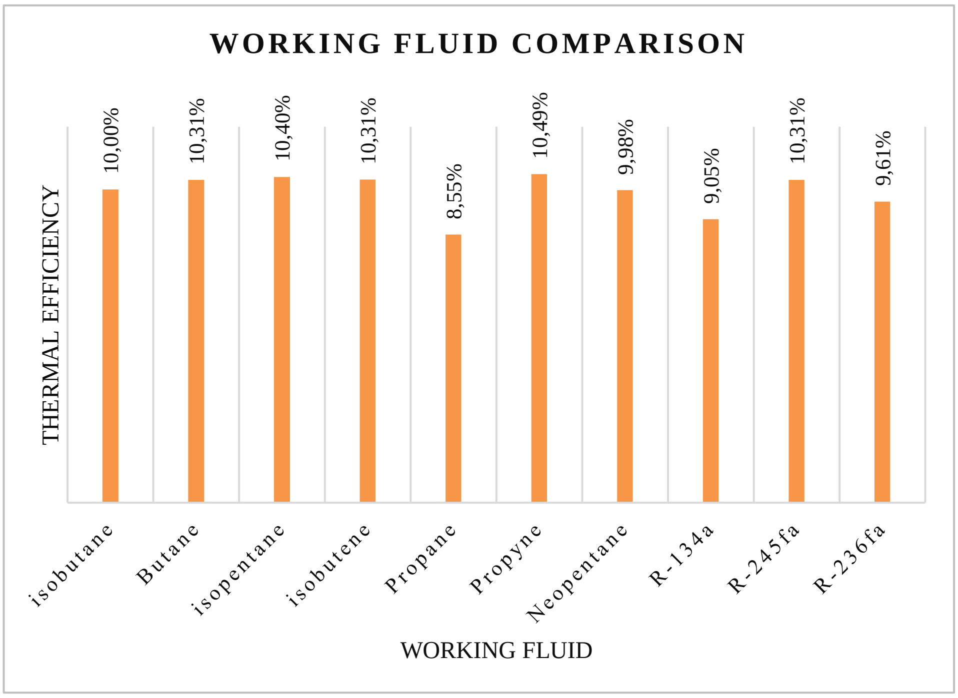

Figure 9. Working fluids comparison by thermal efficiency.

It could be seen in Figure 7 and Figure 8, top two working fluid are Propyne and Isopentane. The two working fluids can generate respectively 2.25 and 2.0 MW of electricity. Based on its thermal efficiency, the two working fluids also show good values, 10.49% and 10.40%. However, it turns out that the two working fluids have different types. Isopentane is a dry type working fluid, while Propyne is a wet type working fluid. It means that at the outlet side of the ORC turbine, the isopentane was in superheated vapor state meanwhile Propyne was in mixed-phase because it will fall inside the vapor dome. It can also be a consideration in the selection of working fluids, because if the working fluid on the outlet side of the turbine is in the mixed phase, it can more quickly damage the turbine blade.

4.2. Discussion

In this study, Pinch point variables are set at a certain value. The Pinch Point value is set at 5°C by referring to the results of previous research. The determination of the value of 5°C is expected to be an applicable value, especially in the geothermal field in Indonesia. So that in fact further research is needed which focuses on the value of applicable Pinch Points especially in Indonesia.

In addition, to find out the number of capital costs for developing ORC in this geothermal field, more detailed calculations are needed, especially in the sizing section of the heat exchanger. In this study, several variable values of heat exchangers are still determined based on assumptions or referring to previous research. Therefore, this research is a general description or a preliminary study of the applicability of the binary cycle for bottoming unit of this specific geothermal power plant, especially from the Engineering side or the thermodynamic calculation side regarding the possibility of reusing the residual heat from a geothermal power plant with back pressure turbines in a geothermal field. In the future, more detailed research is needed on each component in the ORC thermodynamic cycle.

5. Conclusion

The Organic Rankine Cycle (ORC) can be used to utilized wasted steam from two units of back pressure turbine in Flores, Indonesia. The ORC model made in this study, which uses an exhaust steam with 2435 kJ / kg enthalpy as its heating fluid, is capable to generate power up to 2.25 MW. The choice of working fluid is critical in designing ORC. Apart from the thermodynamic side, environmental aspects are also an important factor in the selection of working fluids. Therefore, in this study although R134a, R245fa, and R236fa look good enough from their thermodynamic properties, they are found to be bad for the environment when viewed by the GWP or Global Warming Potential values. The best working fluids in this study are Propyne and Isopentane with 2.25 and 2 MW generated respectively. These working fluids also have high thermal efficiency, which are 10.49% and 10.40%. However, propyne is a wet type fluid while isopentane is a dry type. This can be taken into consideration because the wet type working fluid will produce a droplet of water at the outlet side of the turbine while the dry type working fluid will be in the superheated vapor condition.

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