AIR COOLED CONDENSER AND WATER COOLED CONDENSER PERFORMANCE COMPARISON, CASE STUDY FOR ORGANIC RANKINE CYCLE FOR WAYANG WINDU GEOTHERMAL FIELD

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ABSTRACT

Injection brine discharged from separators in Wayang Windu geothermal field still has a relatively high temperature (178.5 ºC) to be utilized as the heat source to generate electricity using Organic Rankine Cycle (ORC) system. There are two types of ORC system that has been reviewed, simple ORC system and modified ORC system with recuperator. Recuperator is a heat exchanger that uses heat from working fluids to reduce heat duty of condenser and pre-heater. ORC system needs a cooling system for condenser. Cooling systems that has been investigated are air cooling system and water cooling system. Therefore, there are four scenarios that have been investigated, simple ORC with air cooling system, simple ORC with water cooling system, modified ORC with recuperator and air cooling system, and modified ORC with recuperator and water cooling system.

Methodology used was thermodynamics calculations from ORC system and the cooling system. Air conditions such as dry bulb temperature, wet bulb temperature, and relative humidity has been recorded for every hours, started from 1st of June 2016 until 31st of May 2017. The fluctuation of fan power from ORC has been investigated, which is influenced by ambient air conditions, and will significantly reduce ORC net power. From four scenarios that have been investigated, the greatest electrical energy is produced by modified ORC system with recuperator and water cooling system, that produces 28.792.477 kWh of electricity in a year, where the least electrical energy is produced by simple ORC system using air cooling system, which produces 27.333.512 kWh of electricity, that only has 5,20% of difference. This not too significant differences lead to the need of further researches to decide which scenario is suitable to be installed for Wayang Windu geothermal field, such as land availability, make-up water availability, and economical analysis for each scenario.

Keywords: Organic Rankine Cycle, air cooled condenser, water cooled condenser, recuperator, Wayang Windu.

1. INTRODUCTION

Wayang Windu geothermal field is located in Pangalengan, West Java Province, Indonesia. The map is shown in Fig.1. This field has two-phased geothermal fluids, dominated by water-phased fluid, but has several steam zones that is divided into three areas in the reservoir (Bogie, et.al., 2008). Wayang Windu geothermal field is managed by Star Energy Geothermal Wayang Windu Ltd. (SEG WWL) with total of contract area of 14,400 ha (Afandi, 2012). The first exploration was conducted at 1985, and the Joined Operation Contract is to build geothermal power plant for 400 MW capacity. Wayang Windu geothermal field has produce electricity starts from the year of 2000 with 110 MW capacity (unit 1) and adds up into 227 MW capacity in 2009 (117 MW from unit 2). Unit 3 and 4 of power plant is planned to be added to increase the electricity generation into the total of 354 MW.

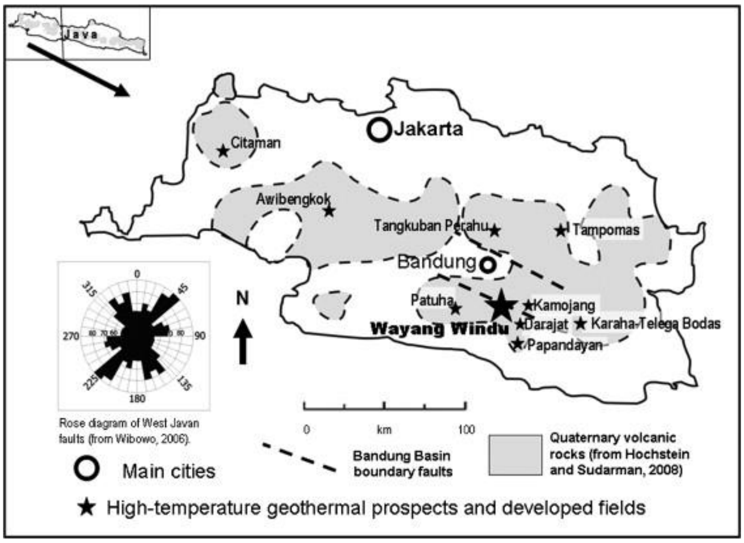

Fig. 1 Map of high-temperature geothermal prospects and developed fields in West Java, including Wayang Windu geothermal field (Bogie, et. al., 2008).

Wayang Windu geothermal field utilizes geothermal fluids into electricity with single flash system technology. This technology uses separator to separate steam and water (brine) before the steam is delivered into the turbine. Brine from separator will be injected back into the subsurface through an injection well to prevent pressure drop in the reservoir. The brine from separator still has a relatively high temperature (178.5 ^{o}C) in the injection well, with mass flowrate of 119 kg/s into WWF-1 and WWF-3. This brine could still be utilized to generate electricity with binary cycle technology. In this research, the brine will be the heat source of binary cycle used to generate electricity, because according to Eliasson, et.al. (2011) for geothermal heat source ranged from 120 to 190 ^{o}C, it is best to use binary cycle to convert the heat into electricity. The binary cycle used in this simulation is Organic Rankine Cycle (ORC). In the simulation, the ORC is placed in the injection pipeline, near injection well to prevent silica scaling from pressure and temperature drop that might occurred in the pipeline. The schematic design is shown in Fig. 2.

There are two types of ORC that would be simulated, simple ORC system and modified ORC system with addition of recuperator. Recuperator is a heat exchanger that use the excess heat of working fluid in ORC to reduce the work needed by pre-heater and cooling system in condenser. In this research, the main focus is to simulate the effect of surrounding air condition in a year into ORC cooling system performance. This effect would be analyzed to determine which cooling system and ORC system scenario has the best performance, if it is observed from the lowest parasitic load consumed by the cooling system itself. The lowest parasitic load will give the highest ORC capacity and also the highest electrical energy produced in a year.

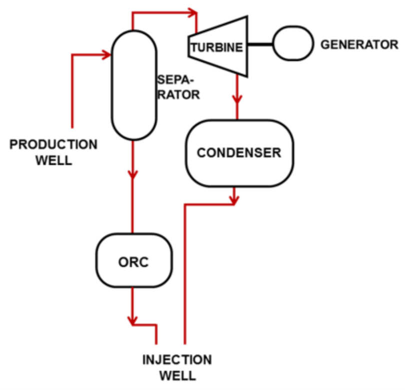

Fig. 2 Schematic of ORC placement in Wayang Windu geothermal power plant system.

There are several type of condenser for geothermal power plants as shown in Fig. 3.

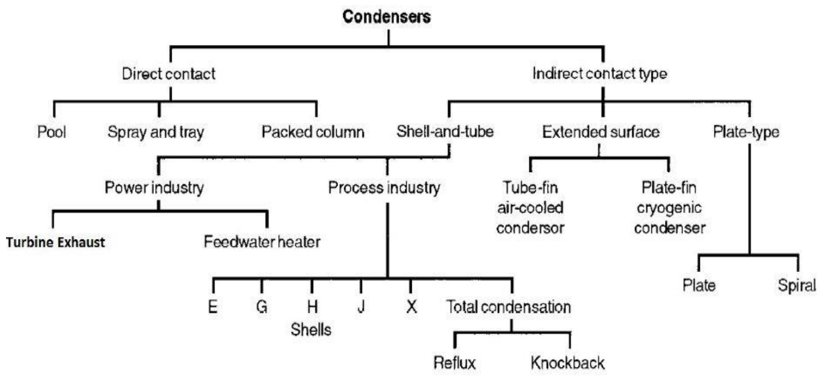

Fig. 3 Types of condenser for geothermal power plants (Najafabadi, 2015).

In this research, there are two types of condenser that will be simulated, those are shell and tube heat exchanger and tube-fin air cooled condenser. The shell and tube heat exchanger will use water cooled condenser. The water cooled condenser is a circulating water system that uses induced draft cooling tower as shown in Fig. 4. The air cooled condenser is extended surface tube-fin condenser consisted of two A-shaped plates with forced draft fan as shown in Fig. 5.

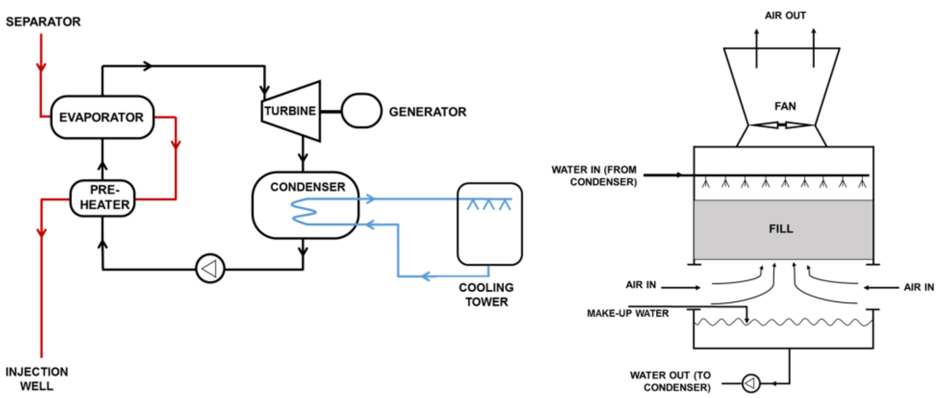

Fig. 4 ORC with shell and tube condenser using water cooled system (left) with cooling tower (right).

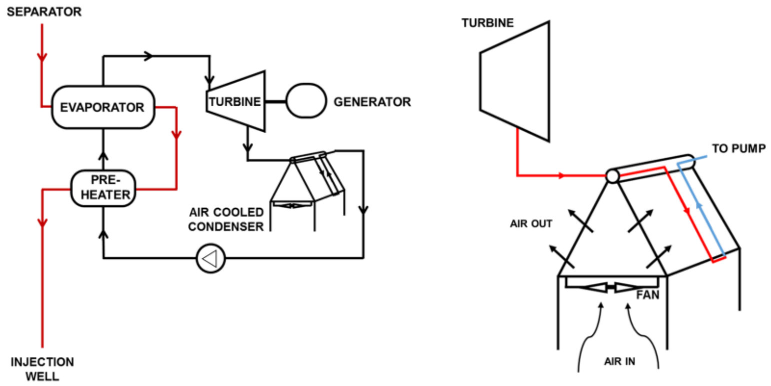

Fig. 5 ORC with air cooling system (left) using tube-fin air cooled condenser (right).

2. METHODS

Method used in this research is to make simulation for parasitic load and power and energy output with thermodynamic calculations. The first step is to determine output brine temperature from ORC by calculating minimum temperature allowed to prevent silica scaling. The second step of the simulation is to find optimum turbine inlet pressure of ORC and determine pinch point temperature of evaporator and pinch point temperature of recuperator. The optimum turbine inlet pressure varies for every organic working fluid used. In this research, the working fluid investigated is the best working fluid for ORC from research done by Fuad (2015). The optimum turbine inlet pressure is determined from the highest gross power output produced by a certain working fluid, but with pinch point temperature still be above the pinch point temperature in evaporator (5 ^{o}C). After the highest gross power output is calculated, the parasitic load from cooling systems in each scenario will be calculated. The value will fluctuates along the fluctuation of surrounding air condition that has been measured for one year, because the cooling from each cooling system is affected by surrounding air condition. The last output from the calculation is the net electrical energy produced in one year for each scenario. In total, there will be 4 scenarios that would be simulated, those are:

1. Simple ORC with air cooling system
2. Modified ORC with recuperator and air cooling system
3. Simple ORC with water cooling system
4. Modified ORC with recuperator and water cooling system

The assumptions used for this simulation are:

1. ORC types investigated are simple ORC and modified ORC with recuperator.
2. Cooling systems investigated are water cooled and air cooled system.
3. The air cooled condenser type is extended surface tube-fin condenser consisted of two A-shaped plates with forced draft fan.
4. The water cooled condenser type is shell and tube condenser using water cooled system with circulating water system that uses induced draft cooling tower. This system needs make-up water that is assumed to be taken from water source near the power plant.
5. The study and simulation only done for the ORC and cooling system type that is mentioned in

point 1 and 2. The best scenario will be determined by the highest net electrical energy output in one year.

6. Working fluids used is the best working fluid for ORC from research done by Fuad (2015).
7. Calculation of fluid properties is done using software NIST REFPROP version 9.0.

3. SURROUNDING AIR CONDITION

There are four surrounding air conditions that has been recorded for one year, from 1st June 2016 to 31th May 2017. Those four conditions are:

1. Dry bulb temperature, is the temperature measured with a dry thermometer bulb. This temperature represents real surrounding air temperature at that moment.
2. Wet bulb temperature, is the temperature measured with a wet thermometer bulb. This temperature represents the temperature of saturated surrounding air.
3. Relative humidity is the ratio of partial pressure of water vapor to equilibrium vapor pressure of water at real air temperature.
4. Surrounding air pressure.

The conditions are recorded every 1 hour. In total, there are 8760 value for each air condition parameters in one year. The profile of dry bulb temperature, wet bulb temperature, and relative humidity per hour in a day is shown in Fig 6. From this graph, it can be seen that the temperature rises starting from 8 a.m. and start to decrease again starting from 15 p.m., which is the opposite of relative humidity, where it's value decrease at 8 a.m. and increase at 15 p.m., so the air is more humid at night and more dry in the morning. The profile of average value of these three parameters each month in one year is shown in Fig. 7. These parameters are recorded in West Java area, Indonesia, which has a tropical climate with rainy season on October to March and dry season on April to September. This profile might be affected by the season, but it would need further research to prove this hypothesis. This profile would be analyzed if it has a relation or same profile with net electricity power and energy produced by ORC.

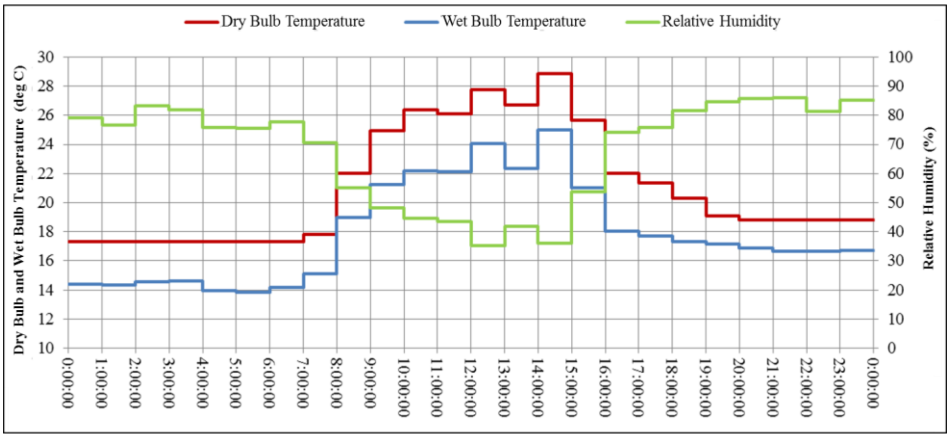

Fig. 6 Profile of dry bulb temperature, wet bulb temperature, and relative humidity per hour in a day.

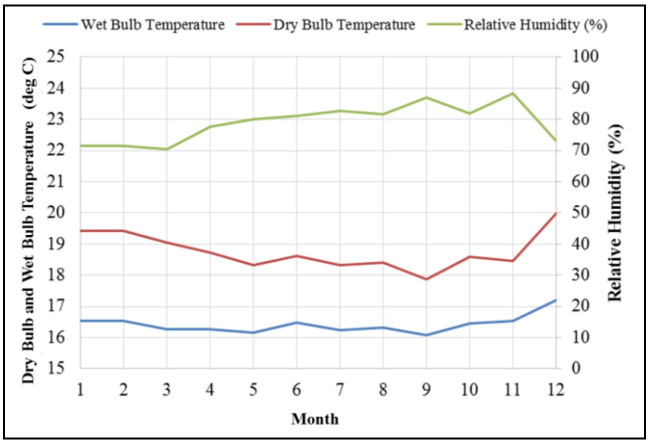

Fig. 6 The profile of average value of dry bulb temperature, wet bulb temperature, and relative humidity each month in one year.

4. NET POWER AND ENERGY CALCULATION

To calculate the net electrical power and energy for each scenario, first is to find minimum outlet temperature for ORC that is limited to temperature to prevent silica scaling, using equation:

$$\log Csat = -\frac{731}{Tsat} + 4.52$$

Where $Csat$ is concentration of saturated silica (mg/kg) and $Tsat$ is temperature of silica saturation (°C). Then the Silica Saturation Index (SSI) follows the equation:

$$SSI = \frac{C}{Csat}$$

Where C is concentration of silica measured in the brine (mg/kg). With these two equations, $Tsat$ for a certain value of measured silica concentration can be determined with selected value of SSI. Value of $Tsat$ will be used for minimum brine outlet temperature from ORC.

After ORC outlet temperature has been determined, next is to calculate the gross electrical power from each scenario. The equation used for power in produced in turbine, power needed for cooling in condenser, and power consumed by feed pump is:

$$Q = \dot{m}_{WF}\,\Delta h$$

Where Q is power in kW, $\dot{m}_{WF}$ is fluid mass flowrate in kg/s, and Δh is difference of fluid enthalpy in input and output condition of the components in kJ/kg. For power needed by working fluid in pre-heater and power given by geothermal brine in pre-heater and evaporator, the equation is:

$$Q = \dot{m}_{WF}\,C_p\,\Delta T$$

Where Cp is heat capacitance for fluid in kJ/kg.K, and ΔT is difference in fluid temperature in input and output condition of the component in K. For power needed by working fluid in evaporator, the equation is:

$$Q = \dot{m}_{WF} \, L_v$$

Where L_v is latent heat for working fluid vaporization in evaporator in kJ/kg. These value of power would need to be multiplied by efficiency of each components to get more realistic values. The equation for net power ($Qnet$) produced (in kW) is:

$$Q_{net} = Q_T - Q_P - Q_{CS}$$

Where Q_T is gross turbine power, Q_P is power consumed by feed pump, and Q_{CS} is power consumed or needed by cooling system. Power given by geothermal brine follows the equation:

$$Q_B = Q_{PH,B} + Q_{E,B}$$

Where $Q_{PH,B}$ is power given by brine to working fluid in pre-heater and $Q_{E,B}$ is power given by brine in evaporator. Thus, the thermal efficiency of system follows equation:

$$\eta_{system} = \frac{Q_{net}}{Q_B} \times 100\%$$

For air cooled condenser, the equation follows:

$$Q_c = \left(G \; dbt_{out} \; c_{p,air} + G \; w_{out,ACC} h_{out,ACC}\right) - \left(G \; dbt_{in} \; c_{p,air} + G \; w_{in,ACC} \; h_{in,ACC}\right)$$

Where Q_C is power needed for cooling (thermal load) in condenser, dbt_{in} and dbt_{out} is dry bulb temperature in and out of condenser (K), $c_{p,air}$ is heat capacity of surrounding air (kJ/kg.K), $w_{in,ACC}$ and $w_{out,ACC}$ is specific humidity of air when enters and exit the air cooled condenser (kg of water vapor per kg of dry air), $h_{in,ACC}$ and $h_{out,ACC}$ is enthalpy of surrounding air when enter and exit the air cooled condenser. Air flowrate entering the condenser (kJ/kg), G (kg/s), follows the equation:

$$G = \frac{P_a}{R_a \; dbt_{in}} \frac{Q_{fan}}{a}$$

Where P_a is partial pressure of dry air (Pascal), R_a is ideal gas constant per relative molecule mass unit of air (J/kg.K), Q_{fan} is power needed to rotate fan (W), and a is constant which value depends on geometry of the fan.

For water cooled condenser with cooling tower, the equation follows:

$$\dot{m}_{cw,in} \; h_{cw,in} + G \; dbt_{in} \; c_{p,air} + G \; w_{in,CT} \; h_{in,CT} + x \; h_{mw} = G \; dbt_{out} \; c_{p,air} + ((G \; w_{out,CT} + x) h_{out,CT} + (\dot{m}_{cw,in} - x) h_{cw,out}$$

Where $\dot{m}_{cw,in}$ is mass flowrate of cooling water entering cooling tower (kg/s), $h_{cw,in}$ and $h_{cw,out}$ is enthalpy of cooling water enter and exit the cooling tower (kJ/kg), $h_{in,CT}$ and $h_{out,CT}$ is enthalpy of air enter and exit the cooling tower (kJ/kg), x is flowrate of make-up water (kg/s), h_{mw} is enthalpy of the make-up water (kJ/kg), and $w_{in,CT}$ and $w_{out,CT}$ is specific humidity of air when enters and exit the cooling tower (kg of water vapor per kg of dry air). The air flowrate enter the cooling tower, G, has the same equation with G for air cooled condenser.

5. RESULT AND ANALYSIS

According to Nazif, et.al. (2015), SSI limit in geothermal field is usually 1.2 – 1.5. With the equation for calculating saturation temperature of silica, the result is 125 ^oC. To maintain the temperature not too close to scaling temperature, the outlet ORC temperature used is 130 ^oC for measured silica concentration in brine 723 mg/kg.

Temperature and mass flowrate of brine is 178.5 ^oC and 119 kg/s. For the 1st and 3rd scenario, the turbine inlet pressure is 29.32 bar abs, and the power output before deducted by cooling systems power needed is 3388.60 kW with thermal efficiency 13.59%, using Cis-butene as working fluid. For the 2nd and 4th scenario, the turbine inlet pressure is 20.00 bar abs, and the power output before deducted by cooling systems power needed is 3446.82 kW with thermal efficiency 13.83%, using R245ca as working fluid.

After being deducted for power consumption of each cooling system for every hour, the power produced every hour for each scenario is shown in Fig. 7. The blue line represents the power output every hour, the yellow line is the average power output every day, and red line is average power output every month. The following table will show the total electrical energy produced in one year from each scenario.

Month	**1st scenario**	**2nd scenario**	**3rd scenario**	**4th scenario**
Total energy (kWh) in one year	27,333,494	27,867,018	28,250,848	28,792,510

As we can see from the gross power output before being deducted by cooling system power needs, the modified ORC power output is higher than simple ORC, with difference about 1.7%. From the average power output for each scenario, the highest comes from the 4th scenario with average power output of 3300 kW, and the lowest comes from the 1st scenario with average power output of 3130 kW. The pattern of energy consumed by cooling system each month has the same pattern with average of relative humidity per month in one year as shown in Fig. 8, where blue line represents average value of relative humidity each month. This shows us that surrounding air condition really affect the performance of cooling systems in ORC.

From the total energy output, the highest energy output comes from the 4th scenario, which is modified ORC system with water cooled condense, however, the difference from the least electrical energy produced (by 1st scenario, simple ORC with air cooled condenser) is only about 5.2%. Because of this value differences are not too significant, it is recommended to do further researches to decide which scenario is suitable to be installed for Wayang Windu geothermal field, such as land availability, make-up water availability, and economical analysis for each scenario.

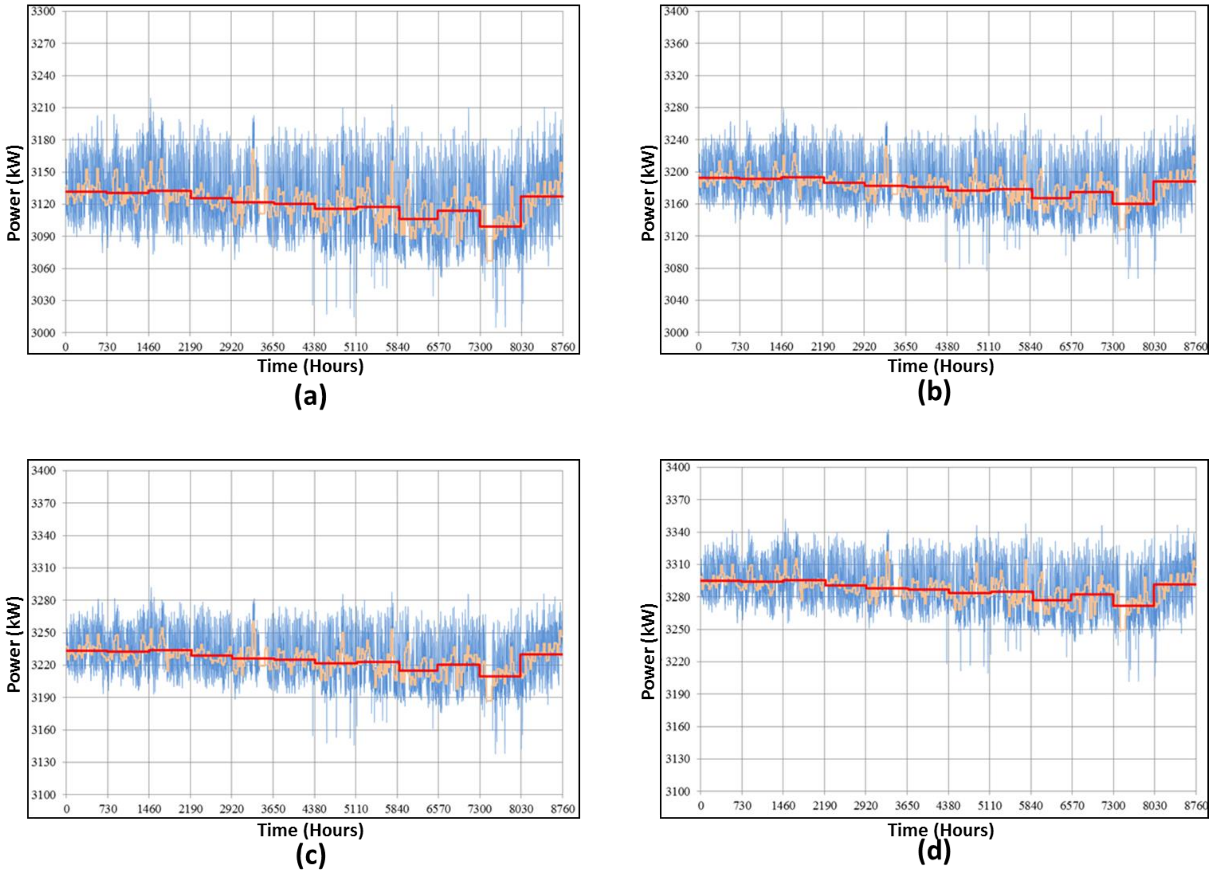

Fig. 7 The profile of output power in one year for the 1st scenario (a), 2nd scenario (b), 3rd scenario (c), and 4th scenario (d).

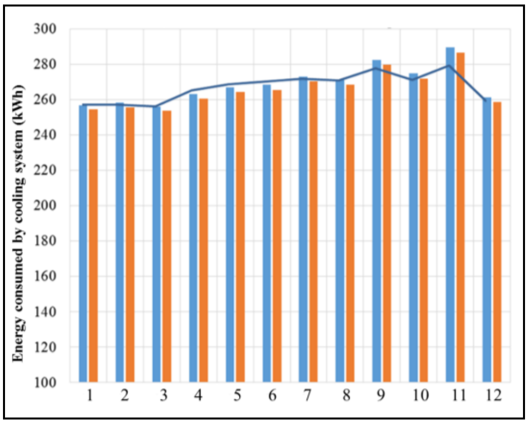

Fig.8 Similar pattern in energy consume by cooling systems per month and average relative humidity each month (blue line).

6. CONCLUSIONS

From simulation and analyses in this research, it is concluded that:

1. ORC modified with recuperator has better performance than simple ORC. It is shown from the net power output from modified ORC (3.45 MW) is higher than net power output from simple ORC (3.39 MW), however, the difference is not too significant (1.70%).

2. For Wayang Windu geothermal field, performance of water cooled condenser is better than air cooled condenser. This is concluded from the electrical energy output from system with water cooled condenser is higher than energy output from system with air cooled condenser.
3. For Wayang Windu geothermal field, from electrical energy output, the highest energy output comes from modified ORC system with water cooled condense, however, the difference from the least electrical energy produced (simple ORC with air cooled condenser) is only about 5.2%, thus, it is recommended to do further researches to decide which scenario is suitable to be installed for Wayang Windu geothermal field, especially economic analysis for each scenario.

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