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Study on Binary Cycle Power Plant Optimization of PLTP Tulehu Ambon with Aspen HYSYS

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Abstract. Ambon Island has potential geothermal energy resources, one of them is geothermal energy in Tulehu where it is managed by PT. PLN has carried out exploration drilling, but the results of the exploration well test results obtained are low temperature and low pressure, so that cannot use conventional power plants. One of the technologies that can be used in this case is the binary cycle. The binary cycle can be used for low temperature geothermal fluid by using the working fluid to drive a turbine. The purpose of this research is to optimize power output by varying the working fluid, turbine inlet pressure and condenser temperature. Working fluids used are isopentane, n-butane and isobutane. The research method uses the Aspen HYSYS and uses REFTROP as a support analysis. Research shows that the power outputs of each working fluid are 2,471.30 kW, 2,052.13 kW and 1,743.09 kW. Working fluid selected used for PLTP Tulehu is isopentane whit net power output is 2,232.55 kW.

Keyword : Geothermal, Binary Cycle, Organic Working Fluid, Aspen HYSYS

INTRODUCTION

Ambon Island is rich in energy, one of the energy sources that can be exploited into electrical energy is geothermal energy [1]. Geothermal can be exploited using Geothermal Power Generation technology to be used as electrical energy [2]. One of the geothermal energy sources is in Tulehu [3]. Tulehu is located in Salahutu, Maluku Tengah at an 100-150 m above sea level [4].

PLTP Tulehu is operated by PT Perusahaan Listrik Negara (PT PLN) and was carried out exploratory drilling. One of the wells drilled is TLU-01 which has been well tested and the result has low pressure and low temperature [5]. This causes the PLTP Tulehu to not be developed using conventional generators [3]. Therefore, alternative steps are needed to be utilized. One of the technologies widely applied for low temperature geothermal power plants is binary cycle [6].

The binary cycle is a power generation technology that can be utilized for low temperature geothermal fluids [7]–[9]. In a binary cycle power generation system, the turbine is not driven directly by geothermal steam but from the working fluid [8], [10], which has received heat transfer in a heat exchanger [11].

From the problems mentioned above, PLTP Tulehu powerplant can be developed using binary cycle generator technology. In this research, the writer tries to optimize the working fluid variations, the turbine inlet pressure (TIP) and condenser inlet temperature.

STUDY LITERATURE

Binary Cycle

Binary Cycle used for low to medium reservoirs temperature [12]. Generally using a heat source with temperatures from 70 °C to 170 °C [13]. In conventional geothermal power plant technology, the only heat source that can be used is steam from the well, while in the binary cycle, the working fluid is used [9]. In a binary cycle, the turbine is not driven directly by steam from the geothermal fluid but by steam from the working fluid with a lower boiling point [8]. The use of working fluid is because geothermal fluid cannot be used directly to drive a turbine [10]. The heat from the geothermal fluid is used as a heating source which will heat the working fluid and turn it into steam which will turn the turbine [14].

As in **FUGURE 1**, the working fluid used in the binary cycle is geothermal fluid from production wells. Geothermal fluid will carry heat which will then be transferred to a working fluid that has a low boiling point using an evaporator. Then the secondary working fluid will evaporate which will be flowed to the turbine [15].

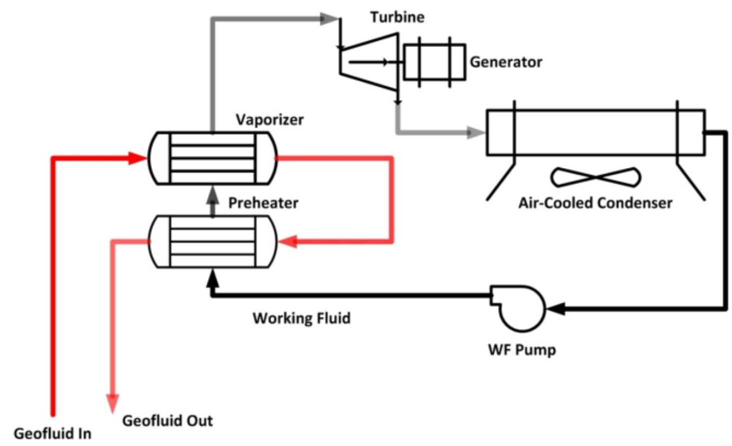

FIGURE 1. Binary Cycle Mechanism [15]

The turbine is coupled to an electric generator which converts mechanical energy into electrical energy. After that, the working fluid will be cooled in the condenser before flowing back into the evaporator so that the cycle repeats itself [15].

Thermodynamic Process

The binary cycle has several main components, namely turbine, condenser, pump, preheater and evaporator [15], [16]. All components can be seen in the schematic diagram in **FIGURE 2 (a).** Geothermal fluid from production wells will transfer heat to the working fluid in the preheater and evaporator [3]. Furthermore, the working fluid will evaporate and have pressure to rotate the turbine. The turbine is coupled to a generator which converts mechanical energy into electrical energy. After that, the working fluid will be cooled in the condenser before flowing into the evaporator, so that the cycle repeats [3].

The thermodynamic cycle in a binary power plant is a closed cycle [8]. The binary cycle consists of two cycles, namely the high temperature cycle (geothermal fluid) and the low temperature cycle (working fluid) [14]. The thermodynamic process of the binary cycle can be seen in **FIGURE 2 (b).**

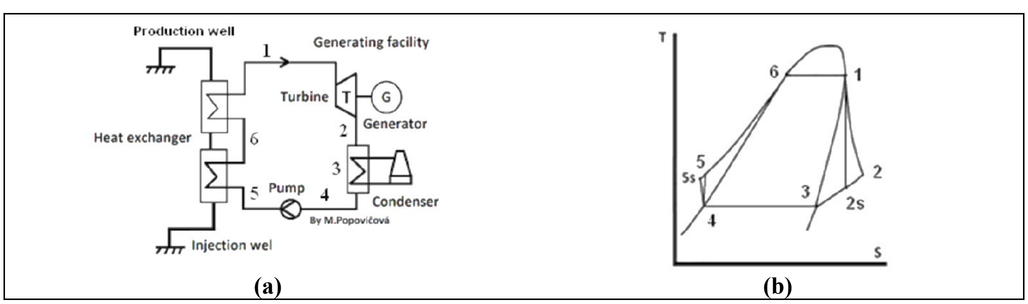

FIGURE 2. (a) Schematic diagram of binary cycle, **(b)** Temperature-entropy (T-s) diagram [17]

Stream Description for:

A = Geothermal fluid enters evaporator
B = Geothermal fluid enters preheater
C = Geothermal fluid enters injection well
1 = Working fluid enters turbine
2 = Working fluid enters condenser
4 = Working fluid enters pump
5 = Working fluid enters preheater
6 = Working fluid enters evaporator

Calculation of the binary cycle in the picture above can be determined by thermodynamic process as follows [17]:

- Turbine process
  Process for the turbine is inlet (stream 1) and outlet (stream 2). Thermodynamic process in the expansion of a turbine such as a steam turbine, assuming neglecting potential and kinetic energy, and the process in adiabatic and steady state. Turbine power output can be determined by equation:

$$W_t = \dot{m}_{wf} \times (h_1 - h_2) \times \eta_t$$

- Condenser process
  Process for the condenser is inlet (stream 2) and outlet (stream 4). Heat transfer in the condenser can be determined by equation:

$$q_{cs} = \dot{m}_{wf} \times (h_2 - h_4)$$

- Pump process
  Process for the pump is inlet (stream 4) and outlet (stream 5). The working fluid pressure drops in the turbine due to the expansion effect. The working fluid pressure is returned to the evaporation pressure in the pump. The power required by the pump can be determined by equation:

$$W_p = \dot{m}_{wf} \times (h_5 - h_4) \times \eta_p$$

- Preheater process
  Process for the preheater is inlet (stream 5) and outlet (stream 6). Heat transfer occurs from the geothermal fluid to the working fluid in the heat exchanger. The pre-heater provides heat to raise the working fluid to the boiling point. The average heat transfer by the preheater to the working fluid can be determined by equation:

$$q_{ph} = \dot{m}_{wf} \times (h_6 - h_5)$$

- Evaporator process
  Process for the evaporator is inlet (stream 2) and outlet (stream 3). The average heat transfer by the evaporator to the working fluid can be determined by equation:

$$q_e = \dot{m}_{wf} \times (h_1 - h_6)$$

Working Fluid

The use of working fluid is because geothermal fluid cannot be used directly to drive turbines [18]. Working fluid is a fluid that has energy to do work on mechanical equipment [2]. In the binary cycle the working fluid used is an organic working fluid [19], then therefore binary cycle is also called organic rankine cycle (ORC) because it has similarities with the Rankine cycle [20]. Working fluid of the rankine cycle is water, while the binary cycle uses the organic fluid [20]. Organic working fluid is used because it has a lower boiling point than water [19].

The working fluid is the most important factor determining the performance of the binary cycle technology [3]. There are various types of working fluids used in the binary cycle, in this study three (three) working fluids were used are isopentane, n-pentane and isobutane which have their respective characteristics as shown in **TABLE 1**. can be seen in the table, each working fluid has different thermodynamic properties.

TABLE 1. Thermodynamic properties of isopentane, n-pentane and isobutane

Working fluid	Critical Temperature (° C)	Critical Pressure (mPa)	Boiling Point (° C)
Isopentane	187.8	3.685	27.8
n-butane	150.8	3.409	-1
Isobutane	135.92	3.718	-11.7

RESEARCH METHODS

This research is a field case study in which field data were obtained at the PLTP Tulehu Ambon, which is located in Tulehu, Maluku Tengah, Maluku, Indonesia. REFPROP version 9 used for analysis thermodynamics of each working fluid and Aspen HYSYS version 8.8 used to create a binary cycle model and perform simulations to optimize and obtain power output. Turbine inlet pressure (TIP) and condenser temperature are varied at a constant mass flow rate of working fluid to maximize the power of each working fluid. The three (3) working fluids used are isopentane, n-butane and isobutane.

In completing this using several steps, briefly as in **FIGURE 3**. The first step is to analyze the condition of the working fluid entering the turbine. Analysis of the condition of the working fluid entering the turbine is carried out to obtain a range of pressure values for each working fluid entering the turbine. The pressure range of the working fluid entering the turbine will have different values, because each working fluid has its own characteristics. This analysis is needed to ensure the working fluid is in a vapor phase condition to be able to drive the turbine [21]. Calculation of thermodynamic properties of working fluid using REFPROP software (Garg et al., 2013). To get the tip value, two parameters are input into the REFPROP. In this study, input used is 100% fraction of steam and maximum temperature limit is 100 º C (below the temperature of the geothermal fluid). REFTROP will perform the calculation automatically.

The second stage is the calculation of the simulation model. Aspen HYSYS version 8.8 used in this research. In the simulation, equipment components and streams are created as shown in **FIGURE 2**. Fluid condition and operation data input is also performed. Variations of conditions are also entered into the model to perform cycle optimization based on variations in tip and condenser temperature. The tip is obtained based on the analysis of the condition of the working fluid entering the turbine according to the previous stage. Variations of condenser temperature are 35 º C, 40 º C and 45 º C. After all the data is entered, the simulation can be run.

Output of Aspen HYSYS is the power output obtained at various conditions for each working fluid. Besides that, the obtained power required by the cycle (such as a pump) is obtained. That way, the net power output can be obtained, as a reference in the selection of working fluid in this research.

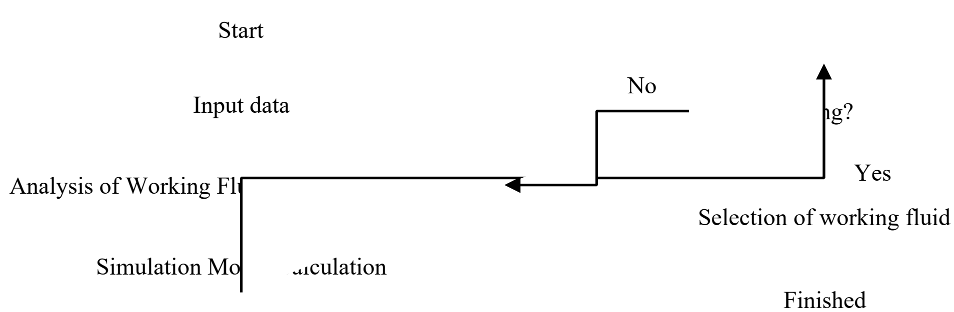

FIGURE 3. Flow chart

RESULT AND DISCUSSION

Analysis of Working Fluid Conditions Entering Turbine

The working fluid used in this study has a critical temperature exceeding the temperature of the geothermal fluid as in **TABLE 1**. Therefore, an analysis of the condition of the working fluid entering the turbine was carried out to obtain the value of turbine inlet pressure (TIP) for each working fluid. The working fluid entering the turbine must be saturated steam, if there is a liquid phase it will be a problem in the turbine [21]. Therefore, the working fluid phase entering the turbine is conditioned at a fraction of 100% with a maximum temperature limit below of geothermal temperature (100 º C). Besides that, the critical temperature also has a significant effect on the pressure [22]. By using the calculations in the REFTROP, the range of allowable TIP values for each working fluid can be seen in **FIGURE 4**.

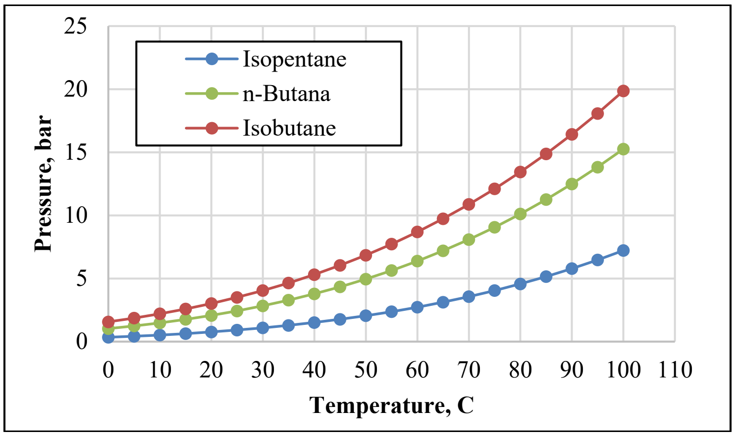

FIGURE 4 TIP Conditions each working fluids

As shown in **FIGURE 4**, at the same temperature value to reach 100% vapor fraction condition with a maximum temperature limit, each working fluid has a different TIP value. Isobutane has the highest TIP compared to other working fluids. This difference TIP value because each working fluid has different thermodynamic properties. Result of analysis of working fluid conditions entering the turbine, the maximum TIP value for each working fluid as **TABLE 2**. The value of TIP maximum for isopentane, n-butane and isobutane are 7 bar, 15 bar and 19 bar.

TABLE 2. Value of TIP maximum for each working fluid

Working Fluid	TIP (bar)
Isopentane	7
n-butane	15
Isobutane	19

Simulation Model

The process flow diagram is the main determinant in the calculations in the process simulation in Aspen HYSYS. In this study, the components are installed as shown in **FIGURE 5**, it can be seen all components are Turbine, Condenser, Pump, Pre-heater and Evaporator. In running the simulation in Aspen HYSYS, data on fluid and operating conditions are required as input. The binary cycle fluid and operating conditions for the model are set as **TABLE 3**.

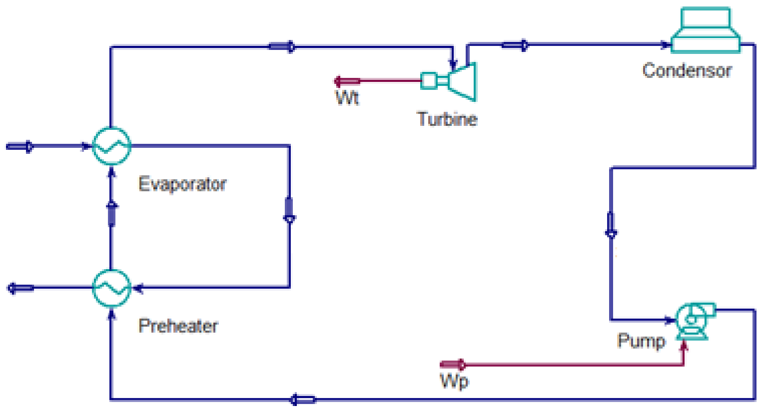

FIGURE 5. Simulation process flow diagram

TABLE 3. Fluid and operating conditions

Parameter	Symbol	Value	Unit
Geothermal fluid temperature	T_{gf}	101.10	° C
Geothermal fluid pressure	P_{gf}	1.01	bar
Geothermal fluid mass flow rate	$\dot{m}_{gf}$	9.146	kg/s
Ambient temperature	T_a	27.7	° C
Working fluid mass flow rate	$\dot{m}_{wf}$	25	kg/s
Turbine efficiency	η_t	90	%
Pump efficiency	η_p	80	%

Simulation Results

The optimal condition of the cycle is obtained based on variations in the value of the turbine inlet pressure and the condenser temperature. Based on the simulation, the correlation between TIP and condenser temperature increases, so the power output will decrease. This is shown in **FIGURE 6**. It can be seen that the isopentane produces the highest power output. Judging from the TIP, isopentane has the lowest value compared to other working fluids. This happens because the characteristics of the isopentane have a high enthalpy value at low pressure so as to produce maximum power [23].

Simulation results obtained the maximum power output of each working fluid as shown in **TABLE 4**. Isopentane produces a power output of 2,471.30 kW at 7 bar TIP and condenser temperature of 35 º C, the net power output generated by the cycle is 2,232.55 kW. N-butane produces a power output of 2,052.13 kW at 15 bar TIP and condenser temperature of 35 º C, the net power output generated by the cycle is 1,809.76 kW. Isobutane produces a power output of 1,743.09 kW at 19 bar TIP and condenser temperature of 35 º C, the net power output generated by the cycle is 1,506.71 kW.

TABLE 4. Simulation result

Working Fluid	TIP (bar)	Power Output (kW)	Net Power Output (kW)
Isopentane	7	2471.30	2232.55
n-butane	15	2052.13	1809.76
isobutane	19	1743.09	1506.71

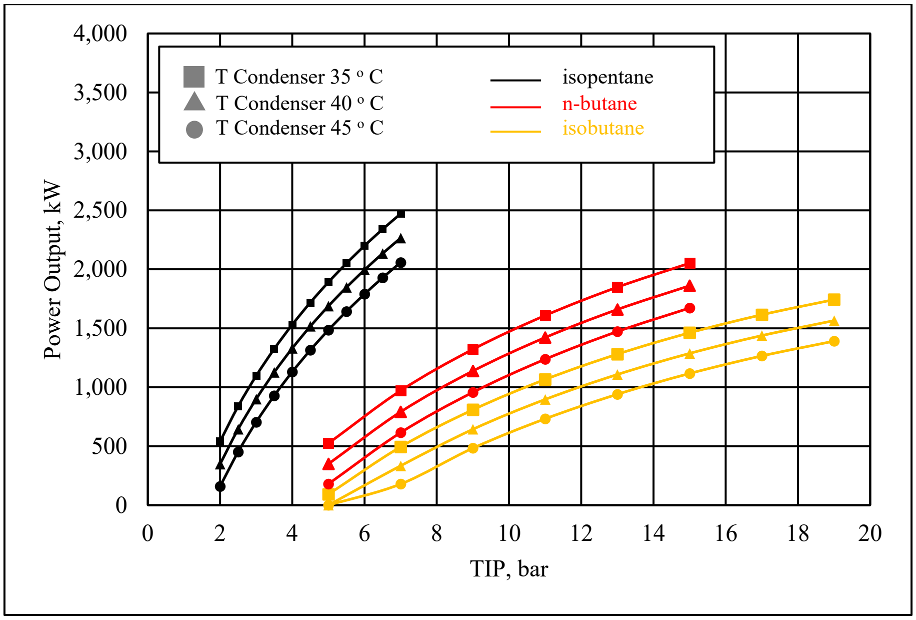

FIGURE 6. Power output result

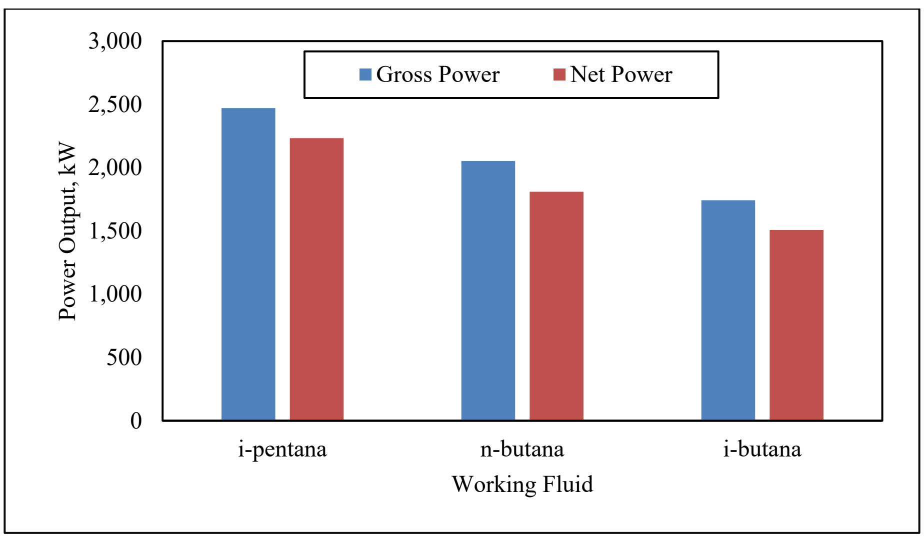

FIGURE 7. Gross vs net power output

Of the three working fluids used, isopentane produces the highest power output compared to other working fluids. While isobutane produces the lowest power output. The comparison of the power output of each working fluid can be seen in **FIGURE 7**.

CONCLUSION

Based on research conducted using isopentane, n-butane and isobutane. The maximum TIP allowed for each working fluid is 7 bar, 15 bar and 19 bar. The maximum power output produced by the turbine is 2,471.30 kW, 2,052.13 kW and 1,743.09 kW. The optimum working fluid used for the binary cycle generator at PLTP Tulehu is isopentane which produces a net power output of 2,232.55 kW.

NOMENCLATURE

Symbol	Description	Unit
h	Enthalpy	kJ/kg
$\dot{m}_{gf}$	Geothermal fluid mass flow rate	kg/s
$\dot{m}_{wf}$	Working fluid mass flow rate	kg/s
P_{gf}	Geothermal pressure	bar
q_{cs}	Specific heat condenser	kJ/kg
q_e	Specific heat evaporator	kJ/kg
q	Specific heat preheater	kJ/kg
T_a	Ambient temperature	^{O} C
T_{gf}	Geothermal fluid temperature	^{O} C
W_p	Power required by pump	kW
W_t	Power output turbine	kW
η_p	Pump efficiency	%
η_t	Turbine efficiency	%

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