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Exergoeconomic analysis and optimization of a combined double flash – binary cycle for Ulubelu geothermal power plant in Indonesia

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Abstract. In this paper, the combination of double-flash and binary cycles for Ulubelu geothermal power plant is proposed and optimized by using the Matlab software. This proposed system uses real data and properties of brine exploited from the Ulubelu geothermal well in Indonesia and four working fluid candidates, namely n-Pentane, R141b, R123 and R245fa are used in binary cycles. Optimization using a multi-objective genetic algorithm with an exergoeconomic approach is applied to find out the proposed system performance from both thermodynamic and economic point of view. In the optimization procedure, the exergy efficiency and total specific cost of output power become objective functions while the first flash pressure, second flash pressure and Organic Rankine Cycle (ORC) turbine inlet temperature are selected as constraints. The system performance proposed in this paper is compared with the performance of the existing system. The results show that n-pentane is the best working fluid where multi-objective optimization indicates that the system can generate 63.54 MW of power with thermal and exergy efficiencies of 17.59% and 65.26% and specific cost of 1.7049 USD / GJ at the selected optimal design point. Compared to the existing system, there is a significant improvement in performance both from thermodynamic performance and economic performance.

1. Introduction

In recent years, renewable energy sources have been the focus of researchers because in addition to being environmentally friendly, these energy sources can also be quickly restored naturally so they will not run out if managed properly. Renewable energy source is one alternative solution to environmental problems caused by fossil energy. One promising renewable energy source because of its consistency and reliability is geothermal energy [1].

Based on geological condition, geothermal energy source can be divided into vapor-dominated and liquid-dominated. Vapor-dominated generally using dry steam system, while liquid-dominated mostly using flash system [2-4]. Organic Rankine Cycle (ORC) systems are also commonly used to harness the energy contained in liquid-dominated to generate electricity [2, 5-7]. The flash system is advantageous for higher temperature sources while the ORC system can utilize energy from sources that have lower temperatures [2, 8].



Several studies have been conducted related to double flash system and ORC system. Agung [9] proposed a double-flash system for Dieng GPP and compared it with existing single flash systems and concluded that double-flash system power output and exergy efficiency were 29.155 MW and 44.04%, respectively. Dipippo, in 2008, reported that the double-flash plant increased power output by 15-25% compared to a single flash plant under the same geothermal fluid conditions [9, 10]. Shokati et al [3] analyzed and compared the double flash and single flash / ORC cycles for geothermal power plants and reported that the dual flash cycle has a lower power cost.

Ulubelu is one of the geothermal power plant in Indonesia located in Lampung. Ulubelu has a liquid-dominated reservoir and uses a single flash system. Ulubelu geothermal power plant has a temperature and pressure of 179 C and 9.8 bar. With a single flash system, after passing through the separator, the brine coming out of the Ulubelu geothermal power plant is injected back into the reservoir after the precipitation process. Brine still has a mass flow rate, temperature and pressure respectively of 650 tons / hour, 171.48 C and 8.21 bar. In other words, this brine still contains the energy that can be extracted. One way that can be done to extract the remaining energy is by the addition of flash separator (double flash) and ORC.

This study aims to design and propose new configurations of combined flash-binary cycles that efficiently utilize the energy of available heat sources in Ulubelu geothermal field as well as analyze their performance by applying exergoeconomic analyzes. The performance of the proposed system is assessed and compared with the existing cycle from thermodynamic and economic point of view. Matlab software is used to simulate existing cycles and proposed cycles based on design data and actual data. In addition, this software is also used to perform multi objective optimization by using multi-objective genetic algorithm with an exergoeconomic approach is applied to find out the proposed system performance from both thermodynamic and economic point of view.

2. System description and modelling

2.1. System description and assumptions

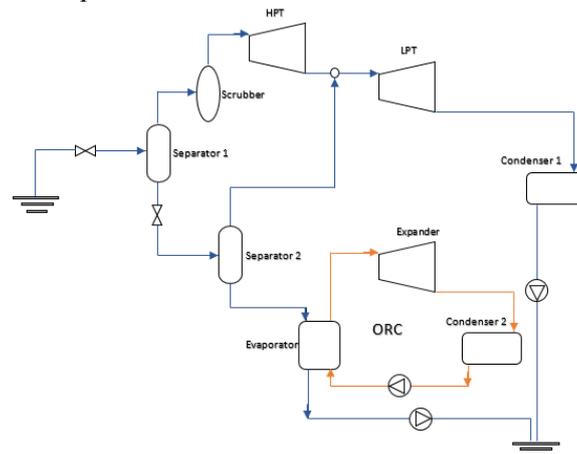


Figure 1. Schematic diagram of the proposed combined flash-binary cycle

Figure 1 shows the schematic diagram of the proposed combined flash-binary cycle. This system is designed by using real data such as pressure, temperature and mass flow rate in Ulubelu geothermal well. This cycle starts from a pressurized steam-brine mixture and high temperature flows through the throttling valve, then separated into two streams namely vapor and liquid brine in separator 1. The vapor is then

flowed directly to the HPT by passing the scrubber to ensure the purity of the vapor. And the liquid brine flowed into the second separator after throttled. The steam that is still in separator 2 is flowed to the LPT after it is mixed with steam coming out of the HPT and then it is injected back to the injection well after it is condensed at condenser 1. Liquid brine from separator 2 which still has temperatures above 100° C, is passed to the evaporator in the binary cycle (ORC) before injection to the injection well. The binary cycle utilizes the thermal energy of the liquid brine coming out of separator 2, which is wasted when not in use. In binary cycles, four working fluids were used in this study to optimize the performance of this combined flash-binary system. The fluids are selected based on available heat sources [11]. The fluids include n-pentane, R141b, R123 and R245fa. Some of the assumptions used are similar to those of Aali et al [2].

2.2. Thermodynamic Analysis

To simulate and evaluate the thermodynamic performance of the proposed system, a computer program was developed by using Matlab software, while the thermodynamic properties of working fluid were calculated using Refprop software. The performance of GPP thermodynamics can be evaluated with thermal efficiency and exergy efficiency. The thermal efficiency and exergy efficiency for the system under consideration is defined as [12, 13]:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{geo}} = \frac{\dot{W}_{net}}{\dot{m}_1(h_1-h_0)} \quad (1)$$

$$\eta_{ex} = \frac{\dot{W}_{net}}{\dot{E}_{geo}} = \frac{\dot{W}_{net}}{\dot{E}_1} \quad (2)$$

$$\dot{W}_{net} = \dot{W}_{HPT} + \dot{W}_{LPT} + \dot{W}_{Expander} - \dot{W}_{ORC_Pump} - \dot{W}_{Pump1} - \dot{W}_{Pump2} \quad (3)$$

2.3. Exergoeconomic Analysis

The specific exergy cost theory methodologies (SPECOC) have been widely used to investigate thermodynamic cycles in exergoeconomic analyzes. To perform an exergoeconomic analysis using the SPECOC method, several equations are used, among them the cost balances equation as follows [2, 14]. For a specific total cost can be calculated by [15]:

$$c_{p_total} = \sum_{i=1}^{n_p} c_{P_i} = \frac{\sum_{k=1}^{n_k} \dot{Z}_k + \sum_{i=1}^{n_f} \dot{C}_{f_i}}{\sum_{i=1}^{n_p} \dot{E}_{P_i}} \quad (4)$$

3. Results and discussion

The objective function in this study is to maximize exergy efficiency and minimize total specific cost. Some real data and assumptions used as inputs in simulations are shown by table 1 and table 2. The parameters chosen as the constraints are first flash pressure (P_2), second flash pressure (P_7) and ORC turbine inlet temperature (T_{18}), with details:

$$\begin{aligned} 800 &\leq P_2 \text{ (kPa)} \leq 980 \\ 300 &\leq P_7 \text{ (kPa)} \leq 700 \\ 100 &\leq T_{18} \text{ (}^\circ\text{C)} \leq 130 \end{aligned}$$

Table 1. Real properties of geofluid available from Ulubelu geothermal wells

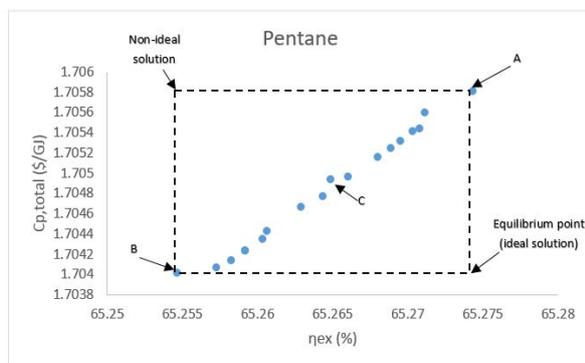
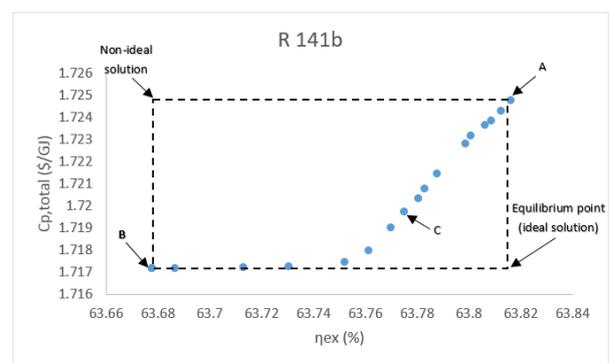
Parameter	Unit	Value
Pressure	kPa	980
Temperature	°C	179
Mass flow rate	kg/s	271.94

Table 2. Input data assumed for the system simulation

Parameter	Symbol	Value
Ambient pressure	P_0 (kPa)	100
Ambient temperature	T_0 (°C)	25
Turbine isentropic efficiency	η_T (%)	85
Annual plant operation hours	τ (hr)	7446
Interest rate	i_r (%)	10
Plant economic life	n (year)	20

3.1. Results of multi-objective optimization

As shown earlier, four ORC fluids namely n-pentane, R141b, R123 and R245fa were selected to maximize exergy efficiency and minimize total specific cost of the system. Optimization is done by using Matlab software and the results are shown in figure 2a-d.

**Figure 2a.** Result of multi-objective optimization for n-pentane**Figure 2b.** Result of multi-objective optimization for R141b

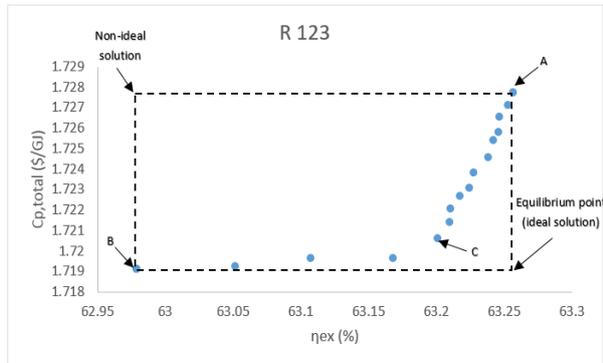


Figure 2c. Result of multi-objective optimization for R123

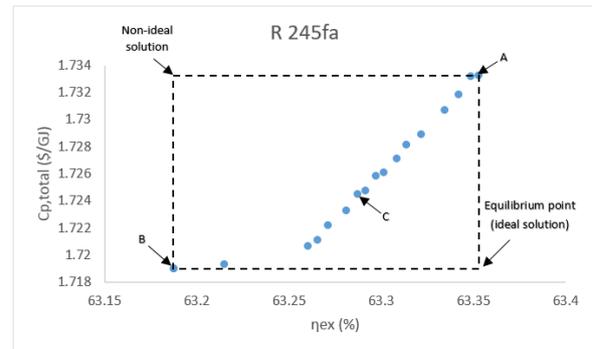


Figure 2d. Result of multi-objective optimization for R245fa

Figure 2a-d shows the Pareto frontier solution for the combined binary flash cycle with four working fluids namely n-pentane (figure 2a), R141b (figure 2b), R123 (figure 2c) and R245fa (figure 2d) as ORC working fluid. Each point of the Pareto frontier is the optimal solution for the two objective functions under consideration: the exergy efficiency and the total specific cost. The best thermodynamic performance for n-pentane (figure 2a) is achieved at point A where the exergy efficiency is 65.274% with the worst economic performance of 1.706 USD/GJ for the specific cost; Meanwhile, the best economic performance is achieved at point B where the specific cost of 1.704 USD/GJ with the lowest exergy efficiency of 65.255 %. Similarly, in other working fluids, point A shows the best thermodynamic performance where there is a maximum value of exergy efficiency while point B shows the best economic performance where there is a minimum value of specific cost. The points A and B values of each working fluid (figure 2a-d) are shown by table 3.

From table 3, it can be seen that from all four working fluids considered, n-pentane becomes the best thermodynamic performance fluid because it produces the highest value of exergy efficiency. Similarly, from the economic side, n-pentane is a working fluid with the best economic performance because it requires the lowest cost.

Table 3. Value of the best thermodynamic and economic performance for each ORC working fluid.

Working Fluids	The best thermodynamic performance (point A)		The best economic performance (point B)	
	η_{ex} (%)	c_{p_total} (USD/GJ)	η_{ex} (%)	c_{p_total} (USD/GJ)
n-pentane	65.274	1.706	65.255	1.704
R141b	63.816	1.725	63.678	1.717
R123	63.257	1.728	62.979	1.719
R245fa	63.353	1.733	63.188	1.719

To determine the point at which all objective functions have the most optimum value requires an approach where the nearest point at the Pareto frontier with the ideal solution (point C) is usually defined as the final optimal point [16]. Using this approach for the system under consideration, the final optimal point for each working fluid can be found in Pareto as shown in Figure 2a-d where the exergy efficiency and specific cost at the final optimum point (point C) for each working fluid can be seen in table 4.

Table 4. Performance comparison of the proposed cycle in this study with existing system at Ulubelu geothermal power plant.

No	Parameters	Unit	Single flash	Combine flash-binary (point C)			
				n-pentane	R141b	R123	R245fa
1	W_{net}	MW	52.38	63.54	61.99	61.55	61.36
2	η_{th}	%	14.73	17.59	17.18	17.04	17.04
3	η_{ex}	%	54.88	65.26	63.78	63.2	63.29
4	c_{p_total}	USD/GJ	1.938	1.7049	1.7197	1.7206	1.7245

Table 4 shows that n-pentane working fluid has a superior value compared to the other three working fluids, which results in an exergy efficiency of 65.26% and a specific cost of 1.7049 USD/GJ. When compared with the existing system (single flash), there is an increase in power of 11.16 MW. The thermal and exergy efficiency of the proposed combined flash-binary cycle is significantly higher than the existing system. In addition, the specific cost is also much lower than the existing system.

4. Conclusions

In this study, a new configuration of combined flash-binary cycle is proposed to utilize the available heat source energy in Ulubelu geothermal field more efficiently. To determine the proposed system performance from a thermodynamic and economic point of view, an exergoeconomic analysis was performed with exergy efficiency and specific costs as an objective function of this analysis. The results show that n-pentane is the best working fluid where multi objective optimization indicates that the system can generate 63.54 MW of power with thermal and exergy efficiencies of 17.59% and 65.26% and specific cost of 1.7049 USD/GJ at the selected optimal design point. Compared to the existing system, there is a significant improvement in performance both from thermodynamic performance and economic performance.

5. Acknowledgment

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