

Energy and exergy analysis of dry-steam geothermal power plant: Case study in kamojang geothermal power plant unit 2

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Abstract. The Government of Indonesia is committed to realize a policy of 35,000 Megawatt (MW) of an additional supply of electricity within 5 years (2014-2019). The projection of this capacity is largely supported by fossil fuel power plants and a small portion of renewable energy. One of the renewable energy which currently has great potential in Indonesia is the geothermal. Therefore, improving the capacity of geothermal is needed to support the policy. The Kamojang is one of the largest geothermal power plant in Indonesia with an installed capacity of 235 MW from 5 generating units. The purposes of this research is to calculate the energy and exergy analysis at Kamojang geothermal power plant. To improve the capacity, exergy analysis can be used by employing the thermodynamic method. In this research, unit 2 of Kamojang's plant is employed. The analysis was examined by using the Engineering Equation Solver (EES) code. The results show the first law of efficiency was calculated at 19.03% and the second law of efficiency at 40.31%.

1 Introduction

The Government of Indonesia is committed to realize the supply of electricity amounting to 35,000 Megawatts (MW) within 5 years (2014-2019). This projection is largely covered by the fossil fuel power plants, such as coal and gas. In supporting this policy, power plants from new and renewable fuels such as wind, hydro, geothermal and sunlight also plays an important role for energy security. Geothermal is one of the energy that has a huge potential in Indonesia. This potential is scattered along volcanic belt paths starting from Sumatra, Java, Bali, Nusa Tenggara, North Sulawesi, and Maluku. Referring to the geothermal investigation conducted by Geological Agency, it has been identified as many as 312 geothermal potential points until 2013 [1]. The total geothermal potential available is 28,910 MW with a total reserve of about 16,524 MW. However, the installed capacity of geothermal power plants until 2014 reaches only 1,403.5 MW or 4.9% from the available potential. Indonesia's geothermal potential is the 2nd largest in the world (13% of world potential), but the installed capacity is only number 3 in the world. In the government projection, geothermal power plants are planned to have an installed capacity of 3,195 MW by 2019 [2]. To support the expansion and upgrading of 35,000 MW capacity, geothermal energy can be one of the optimized energy sources.

Currently there are several geothermal power plants such as Kamojang (235 MW), Lahendong geothermal power plant (80 MW), Sibayak geothermal power plant (12 MW), Salak geothermal power plant (377 MW), Drajat geothermal power plant (270 MW), Wayang Windu geothermal power plant (277 MW), Dieng geothermal power plant (227 MW), Ulubelu geothermal power plant (110 MW), Ulumbu geothermal power plant (10 MW), Mataloko geothermal power plant (2.5 MW) and geothermal power plant Patuha (55 MW) [3]. More details towards the plant in Kamojang, currently has five power plants, units 1, 2 and 3 owned by Indonesia Power and units 4 and 5 operated by Pertamina Geothermal Energy. The production wells that have been developed since 1976 had supplied 1,500 tons / hour of steam for units 1, 2 and 3. These wells suffers a decrease in steam production by about 3% per annum due to a drop in reservoir pressure of an absolute 9.3 bar and a decline in reservoir temperature of 19°C from its original state[4].

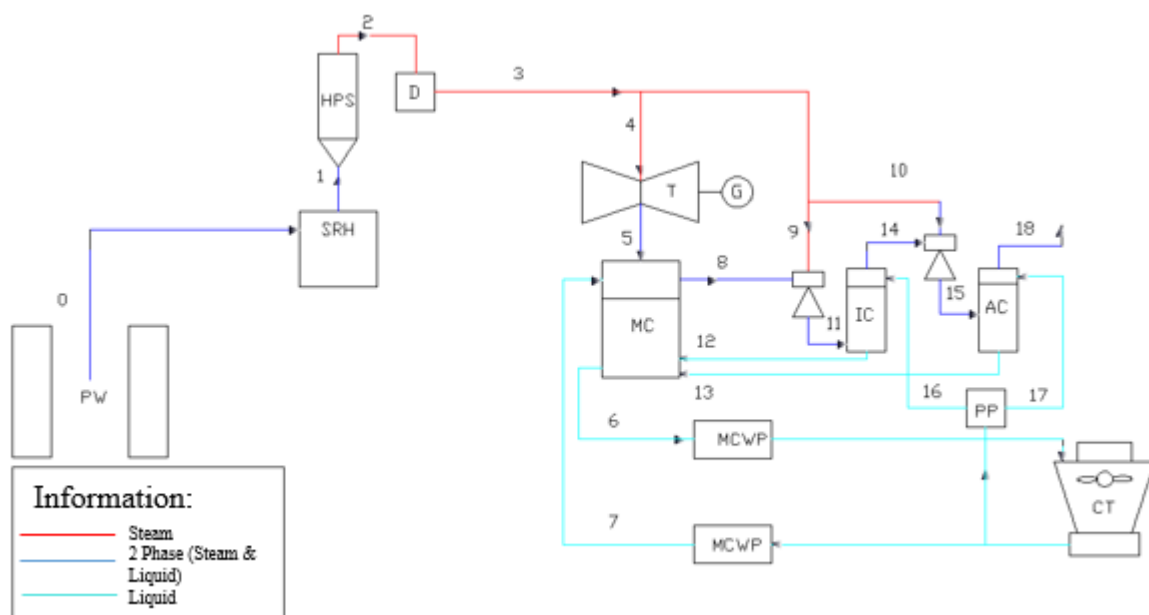
Based on an exergy analysis conducted by Adiprana et al. (2015), Kamojang's Unit 1-2-3 has an exergy system loss of about 104,431 Kw [5]. According to Illah. A. (2016) steam consumption at unit 2 plant in Indonesia Power increased from 240 ton / hour to 350 ton / hour [6]. This is due to the age of the plant which leads to a decrease in the component's performance, resulting in energy losses in the system. These energy losses leads to a decrease in system efficiency.

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In the view of above, one method for optimizing geothermal power plants is through thermodynamic analysis with exergy. The objective of this study is using exergy analysis in evaluating and optimizing unit 2's geothermal power plant in Kamojang. The evaluation and optimization calculations will be performed using the Engineering Equation Solver (EES) code.

2 Method

This study uses numerical approach where data collection is done by taking data that includes data record operation and production within a certain time. The data required in this research are the steam flow rate, temperature and pressure at each state, environmental temperature, power plant power, and other data needed to support the implementation of this research. The data obtained was obtained using software Engineering Equation Solver (EES) with thermodynamic method. The design in the study is shown in Figure 1 below:



Information:

- PW : Production Well
- SRH : Steam Receiving Header
- HPS : High Pressure Separator
- D : Demister
- T : Turbine
- MC : Main Condenser

- MCWP : Main Condenser Water Pump
- IC : Inter Condenser
- AC : After Condenser
- PP : Primary Pump
- CT : Cooling Tower

Fig. 1. Unit 2 Kamojang geothermal power plant main system diagram.

The energy analysis for the generating component can be obtained by the following Eq. (1) and (2) [7].

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \quad (1)$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_o h_o - \sum \dot{m}_i h_i \quad (2)$$

- Where,
- \dot{Q} = Heat entered into the system (kJ/s)
 - \dot{W} = Work generated by the system (kJ/s)
 - \dot{m}_o = Outgoing mass flow (kg/s)
 - \dot{m}_i = Incoming mass flow (kg/s)
 - h_o = Enthalpy output (kJ/kg)
 - h_i = Enthalpy input (kJ/kg)

For the analysis of exergy, the following Eq. (3) can be used:

$$E_X = \dot{m}((h_i - h_e) - T_e(s_i - s_e)) \quad (3)$$

- Where,
- E_X = Exergy (kW)
 - \dot{m} = Mass flow (kg/s)
 - h_e = Surrounding enthalpy (kJ/kg)
 - h_i = Enthalpy input (kJ/kg)
 - s_e = Surrounding enthalpy (kJ/kg.K)

And for the irreversibility (I) of each component's system can be searched by using the following Eq. (4):

$$I = E_{X_i} - E_{X_o} \quad (4)$$

- Where,
- I = Irreversibility (kW)
 - E_{X_o} = Exergy output (kW)

$$Ex_i = \text{Exergy input (kW)}$$

As for knowing the performance of a power plant can use the equation of the second law of thermodynamic as follows (Eq.5) [8]:

$$\eta_{II} = \frac{\sum Ex_o}{\sum Ex_i} \quad (5)$$

Where, $\sum Ex_o$ = Total Exergy Output (kW)
 $\sum Ex_i$ = Total Exergy Input (kW)

3 Unit 2 kamojang plant

Kamojang is one of the geothermal power plants located at Ds. Laksana, Kec. Ibum, Kab. Bandung, West Java province within + 17 km Northwest of Garut or + 42 km Southeast of Bandung, and is located at an altitude of 1640 to 1750 m above sea level. Geographically, it lies at a position of 107°37,5' – 107°48' BT and 7°5,5' – 7°16,5' LS. Unit 2's Kamojang geothermal power plant is managed by PT. Indonesia Power engaged in power generation as well as operation and maintenance services of power plants. Unit 2's Kamojang geothermal power plant operated early 1987 where the installed capacity was 55 MW. The plant is a dry steam plant system with a steam pressure of approximately 6.5 bar. This plant also has several components such as the steam receiving header, separator, demister, turbine, main condenser, ejector first, second ejector, inter condenser, after condenser, main cooling water pump (MCWP) and cooling tower.

4 Results and discussion

4.1 Energy and exergy's system analysis

The value of enthalpy, entropy and energy in each component according to the state is shown in table 1 below.

Table 1. Data and energy analysis.

Component Name	State	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)	Energy (kW)
From Well	0	2,760	6.733	288897
Steam Receiving Header	1	2,760	6.733	89.9
High Pressure Separator	2	2,759	6.738	235.4
Demister	3	2,757	6.754	521.9
Turbine	4	2,253	6.788	58797
Main Condenser	5	2,235	6.962	72545
MCWP	6	549	1.641	956.1
Cooling Tower	7	523.9	1.578	819.6
1 st Ejector	8	2,232	6.77	1542
Motive Steam 1 st	9	2,725	6.693	3820
Motive Steam 2 nd	10	2,725	6.693	2343

Table 1. Cont.

Component Name	State	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)	Energy (kW)
Int-Cond In	11	2,137	5.302	4747
Int-Cond Out	12	204.3	0.6882	219.2
Aft-Cond Out	13	411.5	0.882	301.4
2 nd Ejector	14	2,172	6.343	1244
After-Cond In	15	2,137	5.302	4468
Primary Int-Cond	16	560.1	1.669	12.07
Primary Aft-Cond	17	560.1	1.669	12.07
Final Ejector	18	2,209	6.199	140.9

The main component for a plant is a steam turbine that has 58,797 kW of energy. Though the actual work turbine is 55,000 kW. The Steam Receiving Header (SRH) has an energy amount of 89.9 kW which is the energy lost due to the decrease of enthalpy that exits SRH. Meanwhile, the High Pressure Separator has a total energy of 235.4 kW which shows the energy lost due to the centrifugal force. This results in a pressure drop from the high pressure separator. The demister has about 521.9 kW of energy. In this equipment, there is energy loss because there is a vapor filtering mechanism, for cleaning before entering the turbine. Other components such as the main condenser, cooling tower, inter-condenser and after-condenser have an energy value at 72,545 kW, 4,747 kW and 4,468 kW, respectively. The 1st and 2nd motive steam has an energy value of 3,820 kW and 2,343 kW respectively which is used to suck non condensable gas from the steam into the auxiliary system. Exergy analysis is performed to find out the magnitude, location and causes of irreversibility which consists of the Steam Receiving Header, High Pressure Separator, Demister, Turbine, Main Condenser, Inter Condenser, After Condenser, 1st Ejector, 2nd Ejector and Cooling Tower.

Table 2. Exergy input value, exergy output, irreversibility and exergy efficiency of each component at unit 2 in kamojang.

Component Name	Exergy input (kW)	Exergy output (kW)	Irreversibility (kW)	Exergy Efficiency (%)
Steam Receiving Header	254,432	254,175	257.5	99.9
Separator	254,175	253,404	771	99.7
Demister	253,404	237,590	9,309	96.33
Turbine	245,226	179,545	64,550	73.56
Condenser	192,109	61,682	130,420	32.1
1 st Ejector	5,149	5,063	85.68	98.34
Inter Condenser	5,128	4,661	467.2	90.89
2 nd Ejector	4,904	4,764	139.6	97.15
After Condenser	4,830	4,128	701.9	85.47
Cooling Tower	5,383	5,217	166.4	96.91

Table 2 shows the number of the total of exergy input and output on each component. At SRH the magnitude of exergy input and output is 254,432 kW and 254,175 kW respectively. During operation this component produces an exergy loss of 257.5 kW. This is caused by the venting process found in the vent structure. This tool serves to remove the excess steam that will enter the system. Therefore this risks in the loss of steam. In addition, the irreversibility of SRH is also caused by a steam leakage on 4 inlet pipes, 3 outlet pipes, and 2 safety valves. Steam leaks through the valve packing because the material is made of rubber. This material over time operation will experience stiffness and cracking.

In other components such as the High Pressure Separator, has an irreversibility of 771 kW. This is caused by a centrifugal force. Particles of larger density exits the vortex and hit the separator wall and then falls down to the dust collector. Furthermore, the friction between the vapor and the separator wall resulted in a pressure drop. HPS material also uses rubber packing on its connection, resulting in leakage.

Irreversibility on other components such as the Demister also caused the same thing as HPS and SRH, i.e. rubber material. Meanwhile, in the Turbine, irreversibility caused due to a throttling process on the main stop valve and the governor valve. This process resulted in a pressure drop. During nearly 30 years of operation, the turbine blades also undergoes a plastic deformation due to the presence of solid particles still present in the vapor. This is due to a failed filtering process on the demister. The silica that falls in the steam also affects the turbine's irreversibility. Condensed silica on stage 1 and 2 turbines contributes to the greatest pressure drop. The silica deposit will cause a decrease in the turbine performance and impact on the declining ability of the plant to produce electricity.

The exergy of 192,109 kW contained in the main condenser comes from the remaining steam coming out of the turbine. While the exergy of 61,682 kW that left the condenser comes from the condensed steam and towards the cooling tower. The irreversibility of 130,427 kW of the main condenser comes from the process of condenser and steam heat absorbed by cold water from the cooling tower. The condenser's irreversibility is also influenced by the exhaust steam heat rejection that is the flow of steam from the turbine to the condenser. The heat transfer area of condenser is a direct contact type. The problems that often arise in the main condenser is the blockage and blocking caused by the entry of mud from the cooling tower. This results in the blockage of nozzles on the main condenser. So the water that should be sprayed in spray shape is changed in the form of water film. This resulted in higher condensate temperatures.

The inter condenser and after condenser each have an Irreversibility of 467.2 kW and 701.9 kW respectively. This Irreversibility is due to the occlusion of the nozzle tray and its components. Condensation process at the inter condenser and after condenser use the primary cooling water system which contains a lot of sulfur mud. This sulfur sludge will slowly clog the nozzles contained

in the inter and after condenser. The blockage problem in the nozzle tray can be solved using a mechanical cleaning, but to perform the cleaning, the plant must be in a shutdown condition.

1st ejector and 2nd ejector each have exergy input of 5,149 kW and 4,904 kW and an exergy output of 5,063 kW and 4,764 kW respectively. The Irreversibility of the 1st ejector and 2nd ejector is of 85.68 kW and 139.6 kW respectively. Irreversibility on the 1st ejector and 2nd ejector is due to the blockage of the inlet and outlet hole due to a scaling and age of the components that have been operating for 30 years.

Exergy contained in the cooling tower is of 5,383 kW comes from the water condenser that still have a temperature of 50°C where the water will be cooled in the cooling tower. While the exergy of 5,217 kW that left the cooling tower comes from condensed steam and towards the cooling tower. The irreversibility of the cooling tower of 166.4 kW comes from the hot water absorbed by the cold water and the help obtained by the fan from the cooling tower.

Based on the exergy input, exergy output and exergy's irreversibility, it can be known that the excessive efficiency of each component of the system is shown in Figure 2 below:

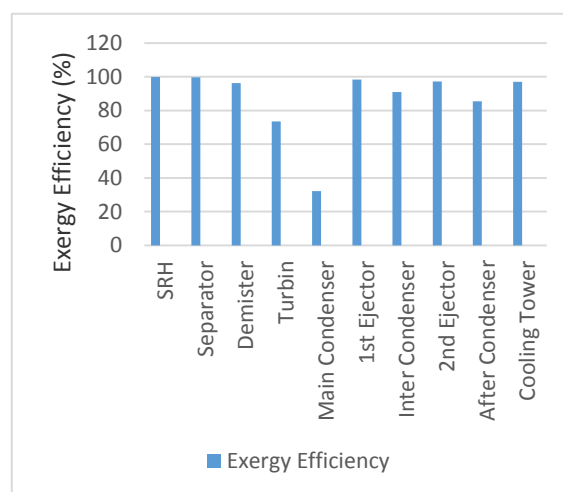


Fig. 2. Exergy efficiency bar chart of unit 2 kamojang geothermal power plant main system.

SRH, separator and demister each have an exergy efficiency of 99.9%, 99.7% and 96.33% respectively. All three components have an exergy efficiency above 95% which means there is not much exergy loss on the component. The exergy efficiency of the turbine shows a value of 73.56%. The exergy efficiency of the main condenser shows the figure of 32.1%. The inter condenser and after condenser each have an exergy efficiency of 90.89% and 85.47% respectively. The 1st ejector and 2nd ejector have an exergy efficiency of 98.34% and 85.47% respectively. The cooling tower component has an efficiency of 96.91%. While the main condenser has the lowest exergy's efficiency compared to the components of the main condenser functioning for the condensation process of steam from the turbine heat.

4.1.1 Grassman Diagram and analysis performance

Figure 3 shows available exergy that goes into the system is of 254432 kW. Not all available exergies can be converted into an electrical energy due to an excess that is lost due to the irreversibility process. The Grassman diagram in Figure 6 shows the magnitude of the lost exergy in the SRH, separator, demister, turbine, main condenser, 1st ejector, inter condenser, 2nd ejector, after condenser and cooling tower of 257.5 kW or 0.10% , 771 kW or 0.303%, 9309 kW or 3.65%, 9550 kW or 3.75%, 130420 kW or 51.25%, 85.68 kW or 0.033%, 467.2 kW or 0.183%, 139.6 kW or 0.054%, 701.9 kW or 0.275% and 166.4 kW or 0.065% respectively and the net power generated is at 102556,72 kW or equal to 40.31% of the total exergy entered into the main system of Unit 2 Kamojang PLTP.

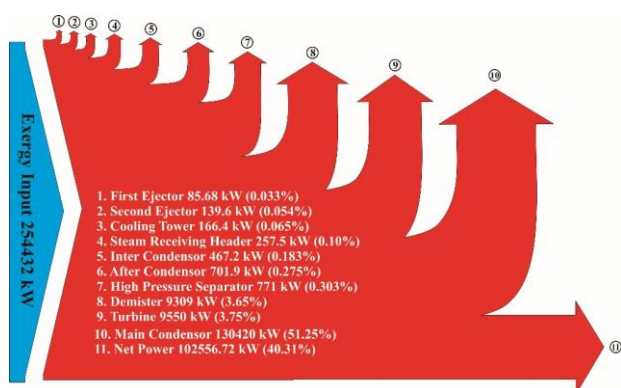


Fig. 3. Grassman diagram of unit 2 kamojang geothermal power plant main system.

Exergy performance analysis shows the net power output, first law efficiency, and second law efficiency in table 3. The net power output on the system is 102,556.72 kW, while the first and second law efficiency is 19.03% and 40.31%, respectively.

Table 3. Exergy performance analysis unit 2 kamojang geothermal power plant system.

Parameter	Performance
Net power output (kW)	102,556.72
first law efficiency (%)	19.03
second law efficiency (%)	40.31

If we compare to other plant, for example in Dieng plant, the Kamojang has higher efficiency. In Dieng it is reported that their first and second efficiency are 11.62% and 36.7%, respectively [9]. The kamojang power plant has higher efficiency since it is a dry steam technology while in Dieng is flash technology. Dry steam technology, the steam from the production well is directed to the tubin and activates the generator to produce electricity [10]. Dry steam power plant is not widely used since the type of vapor-dominated reservoir is rare. In the world there are known 4 geothermal resources with vapor-dominated reservoirs among them are Kamojang, Darajat, The Geysers, Lardarello [11].

5 Conclusions

The result of energy and exergy analysis on Unit 2’s Kamojang geothermal power plant gives information about the amount of energy produced by the turbine at 58,797 kW and the location and magnitude of the irreversibility occurred in the main condenser is at 130,420 kW. The plant shows that the first law efficiency and second law efficiency of 19.03% and 40.31% respectively.

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