Performance improvement of drysteam geothermal power plant by employing bottoming binary system

Nova Dany Setyawan1, Nugroho Agung Pambudi1*, Frandhoni Utomo1, Lip Huat Saw2, Mert Gürtürk3, and Saeid Mohammadzadeh Bina4

1Mechanical Engineering Education, Sebelas Maret University, Jl. Ir. Sutami 36A, Surakarta 57126, Indonesia
2Lee Kong Chian Faculty of Engineering and Science, UTAR, Selangor, 43000, Malaysia
3Department of Energy Systems Engineering, Technology Faculty, Fırat University, 23100 Elazig, Turkey
4Graduate School of Engineering and Resource Science, Akita University, Akita, Japan
*Corresponding author: agung.pambudi@staff.uns.ac.id

Abstract. This study examines on how to improve the performance of dry-steam geothermal power plants in Kamojang by utilizing the binary system. The main data taken in this research is the temperature, pressure and mass flow collected from the plant’s operational data. It is then analyzed using the thermodynamic method and Engineering Equation Solver (EES). Results from the analysis showed that the net power output is about 48,865 kW. The first law efficiency increases from 16.45% to 19.44%, while the second law efficiency increases from 18.69% to 28.75%.

Keywords: bottoming binary system, geothermal power plant, thermodynamics, exergy

1. Introduction

In the last decade, energy consumption has increased exponentially due to rapid population growth. Commission et al. explained that during the period of 2000-2030, energy consumption will increase 1.8% per year worldwide. Meanwhile, in EU countries the rate is estimated at 0.5% per year. In Asian countries, it is around 3% per year [6]. Unfortunately, most of this energy demand is covered through the use of non-renewable energy sources such as petroleum, gas, and coal. Therefore, it impacts the risk of global warming caused by the production of carbon dioxide gas (CO₂) from the burning of fossil fuels [11]. One way of reducing these emissions is to reduce the use of fossil energy and switch to renewable energy.

There are various sources of renewable energy, including wind, water, geothermal, biomass and solar energy. For some countries located in the Ring of Fire, geothermal energy has good potential. These sources make negligible contributions to global warming because of their small emissions. Currently, the New World countries are using 10.4% (10.8 GW) with a potential of 103.6 GW (KESDM, 2016). Pambudi et al. [12] reported in his research that there are six largest countries which utilize geothermal power significantly in their energy mix system: namely USA (3700 MW), Philippines (1870 MW), Indonesia (1924.5 MW), Mexico (1058 MW), New Zealand (1005 MW), and Japan (519 MW).

There are several geothermal power conversion technologies, including flash, binary and dry-steam. This technology is applied based on available resources. Most of the technology used includes flash because most of the reservoir worldwide is water-dominated. For binary, the unit has a large number, but for a lower capacity. Dry-steam power plants are not widely used because they represent the vapor-dominated type of reservoir. In dry-steam technology, hot steam from the production well is directed to spin the turbine.
There are only 4 geothermal plants with vapor-dominated reservoirs worldwide, and among them are Kamojang, Darajat, The Geysers and Lardarello [4], [8]. In this research, we will discuss the performance improvement of a dry-steam plant in Kamojang, Indonesia through utilizing the excess vapor from the vent structure by applying binary technology. The combination of the binary system and a flash geothermal power plant has been widely discussed by researchers. Pambudi et al. [13] investigate this at the geothermal plant in Dieng, Indonesia that shows an increase of first law efficiency and second law efficiency by 13.43% and 41.97% respectively with an additional binary system. DiPippo et al. [5] conducted a similar study at the geothermal plant in Las Pailas, Costa Rica which showed an increase of first and second law efficiency by 16% and 43.7%. El Emam, R. S., et al. [7] conducted a geothermal design study with an additional binary system which showed an increase of 16.37% and 48.8% of first and second law efficiency.

The Geysers is the largest dry-steam geothermal power plant in the world, with an installed generator capacity of 1462 MW [4]. The Kamojang Geothermal power plant is one of the few existing dry-steam geothermal power plants in Indonesia. The plant has an overall system efficiency of 33.86% from 10 production wells [15]. Utilizing the excess of Kamojang’s geothermal steam generates a total power output of 19.9 MW with one stage liquid ring vacuum pump (LRVP) system [14]. Tempesti et al. [17] utilized Heller condenser in the plant and showed an increase of 85% in pump efficiency. Furthermore, in this research, a binary plant will be added to the existing system in Kamojang using the thermodynamic method. The calculation of exergy optimization will be assisted by the Engineering Equation Solver (EES).

2. Site description of Kamojang’s power plant

The geothermal power plants in Kamojang have five plants operated by two companies, which are Pertamina Geothermal Energy (PGE) and Indonesia Power. Units 1, 2 and 3 are owned by Indonesia Power while Units 4 and 5 are operated by PGE. All production wells that have developed since 1976 are owned by PGE. They had supplied steam at a rate of 1,500 tons/hour to Units 1, 2 and 3 of Indonesia Power. The 30-year-old steam-producing plant had decreased in steam production by about 3% annually due to the pressure drop on their reservoir [16]. Based on an exergy analysis conducted by Adiprana, R., et al. [1], Kamojang Units 1-2-3 had an exergy system loss of 104,431 kW and according to Illah [9], steam consumption in Unit 2 at the Indonesia Power UPJP geothermal plant in

![Figure 1. Main System Diagram of Kamojang’s Unit 2 Geothermal Plant](image-url)
Kamojang increased from 240 tons/hour to 350 tons/hour. A schematic diagram of Kamojang’s Unit 2 geothermal plant with a capacity of 55 MW is shown in Figure 1 below.

In Figure 1, there are 18 states showing the steam flow from the plant. State 0 is steam containing water (2 phases) from the production well to the steam-receiving header (SRH). State 1 is a steam containing water (2 phases) from SRH to a high-pressure separator. State 2 is the separated steam resulting from the high-pressure separator to the demister with a decrease of water content in the steam. States 3 and 4 (i.e. dry-steam moisture from waterless demister) will enter the steam turbine. State 5 is the steam resulting from an expansion in the turbine heading towards the main condenser, which converts into a liquid phase. State 6 is condensed water in the main condenser heading towards the cooling tower to lower its temperature. State 7 results from the cooling in a cooling tower which flows into the main condenser. At State 8, that is the non-condensable gas resulting from the 1st ejector pumping the condensation through the main condenser. States 9 and 10 are non-condensable gases and part of the steam derived from the demister goes into the auxiliary system, where it is pumped by the 1st and 2nd motive steam. State 11 which is non-condensable gas and a portion of steam that had been pumped by the 1st ejector and the 1st motive steam into the inter-condenser to cool. The condensation in States 12 and 13 resulted from condensation in the inter-condenser and after-condenser flowing to the main condenser. State 14 is non-condensable gas resulted from the condensation at the main condenser pumped by the 2nd ejector. State 15 is non-condensable gas and a portion of steam that had been pumped by the 2nd ejector and the 2nd motive steam goes into the after-condenser to cool. States 16 and 17 consist of water resulted from the cooling process in the cooling tower, which flows to the inter-condenser and after-condenser to assist the condensation process. State 18 is where non-condensable gas and a portion of steam that cannot be condensed in the after-condenser is discharged to the cooling tower.

References:

VS : Vent Structure   P : Pump   BT : Binary Turbine
E : Evaporator   R : Recuperator   IW : Injection Well
PH : Preheater   ACC : Air Cooling Condenser

Figure 2. Additional Binary System Diagram of Kamojang’s Unit 2 Geothermal Plant
Table 1. Parameter Data of Additional Binary System Kamojang’s Unit 2 Geothermal Plant

| Parameter                          | Data Type      | Value    |
|------------------------------------|----------------|----------|
| Dead State Temperature             | Measured       | 19°C     |
| Dead Starte Pressure               | Measured       | 0.85 bar |
| Mass Flow Steam                    | Measured       | 23.61 kg/s |
| Vent Valve Pressure                | Measured       | 6.5 bar  |
| Pinch-point Temperature            | Design         | 10°C     |
| Different Water Cooling Temperature| Design         | 10°C     |
| Pump Pressure                      | Design         | 7 bar    |
| Feed Pump Isentropic Efficiency    | Design         | 85 %     |
| Turbine Isentropic Efficiency      | Design         | 90 %     |
| Working Fluid                      | Design         | n-pentane |

References:

- PW : Production Well
- SRH : Steam Receiving Header
- HPS : High Pressure Separator
- D : Demister
- T : Turbine
- G : Generator
- MC : Main Condenser
- MCWP : Main Condenser Water Pump
- IC : Inter Condenser
- AC : After Condenser
- PP : Primary Pump
- CT : Cooling Tower
- VS : Vent Structur
- E : Evaporator
- PH : Preheater
- P : Pump
- R : Recuperator
- ACC : Air Cooling Condenser
- BT : Binary Turbine
- IW : Injection Well

Figure 3. Dry-stem - binary combination model
3. Additional plant of binary system for Unit 2

The additional model for a binary system in Kamojang’s Unit 2 has 6 main components: namely the recuperator, water cooling condenser, main condenser, preheater, evaporator and binary turbine; the pump and the vent were structured as additional components. A schematic diagram of the additional binary system in Kamojang’s Unit 2 geothermal plant is shown in Figure 2 below.

In Figure 2, there are 7 states showing the steam flow from the additional binary. State 1 is the working fluid that turned to steam in the evaporator slowing into the binary turbine to move the turbine blades. State 2 is the steam resulted from an expansion in the binary turbine heading towards the recuperator, which a water cooling condenser converts into liquid phase. State 3 is water for condensing the working fluid out of the recuperator that flows toward the water-cooling condenser. State 4 is a cooler that comes from the water-cooling condenser which then flows to the pump. State 5 is the cooler flowing to the recuperator by the pump. State 6 is the working fluid flowing into the preheater to make sure that the working fluid warms up before flowing to the evaporator. State 7 is the working fluid entering the evaporator so that the fluid changes into steam phase which is later required to move the turbine.

4. Dry-Steamp - Binary combination

The binary system utilizes steam from the Vent Structure. This is the components used in controlling unused steam in the event of excess steam in the Steam Receiving Header (SRH). This combination is shown in Figure 3 as follows.

5. Thermodynamic Method

The combination system is solved through the thermodynamics method with the help of Engineering Equation Solver (EES). The mathematical expression of the first law of thermodynamics is described as follows [2]:

\[ \Delta E = Q - W \]  

(1)

The energy change (\( \Delta E \)) is equal to the reduction of the total heat (Q) added to the system, and the work (W) performed by the system. Then, the energy changes can be expanded as follows

\[ \Delta E = m[(h - h_0) + \frac{1}{2} (V^2 - V_0^2) + g(z - z_0)] \]  

(2)

To evaluate the performance of power plants associated with the exergy, the analysis of the second law of efficiency can be used. This can be expressed mathematically throughout the system as follows [2]:

\[ \eta_{II} = \frac{\dot{W}_{net}}{\dot{X}_{in}} \]  

(3)

Where \( \dot{W}_{net} \) generates work by the plant and \( \dot{X}_{in} \) is the total exergy that goes into the plant. The amount of exergy entered into the system can be calculated using the information obtained from the fluid properties at the top of the production well. The second law of efficiency can also be calculated from each component in the system. Using the input and output exergies from the components as given in the following mathematical equations in [3]:

\[ \eta_{II} = \frac{\sum \dot{X}_{out}}{\sum \dot{X}_{in}} \]  

(4)
6. Result and Discussion

The operational data from the geothermal plant components is sought for enthalpy and entropy values using the EES (Engineering Equation Solver) software used for calculation and analysis of energy and exergy of the main system of Kamojang’s Unit 2 geothermal plant.

The main Operational System Data of Kamojang’s Unit 2 Geothermal Plant is shown in Table 2. Table 3 shows the value of enthalpy, entropy and energy rate which is in the main system of Kamojang’s Unit 2 geothermal plant. The main component for the plant is the steam turbine. The steam turbine in table 3 has an energy amount of 58,797 kW which is from the actual work in the turbine and only 55,000 kW is converted into electrical energy.

Steam Receiving Header (SRH) has a total energy amount of 89.9 kW which is the energy lost due to the decrease in enthalpy. The High Pressure Separator has a total energy of 235.4 kW which shows the energy lost from the centrifugal force resulting in a pressure drop from the high pressure separator. The demister has a total of 521.9 kW of energy. The main condenser component has a total of 72,545 kW of energy, the energy at the main condenser is huge due to the energy being in the form of heat derived from the cooled output of the steam turbine. The energy value of the inter condenser and after condenser is at 4,747 kW and 4,468 kW which resulted from the steam condensation derived from the motive steam and part of the steam which is sucked by the first and second level of the gas removal system. The 1st and 2nd motive steam has an energy value of 3,820 kW and 2,343 kW that is used to suck non-condensable gas from steam that entered into the auxiliary system.

| Components       | State | Pressure (bar) | Temperature (°C) | Mass Flow (Kg/s) | Enthalpy (kJ/kg) | Entropy (kJ/kg K) | Energy (kW) |
|------------------|-------|----------------|------------------|------------------|------------------|-------------------|-------------|
| From Well        | 0     | 6.50           | 168.66           | 117.1            | 2,760            | 6.733             | 288,897     |
| Steam Receiving Header | 1 | 6.50           | 168.66           | 117.1            | 2,760            | 6.733             | 89.9        |
| Separator       | 2     | 6.40           | 168.66           | 117.1            | 2,759            | 6.738             | 235.4       |
| Demister        | 3     | 6.11           | 168.66           | 117.1            | 2,757            | 6.754             | 521.9       |
| Turbine         | 4     | 5.52           | 165.38           | 113.5            | 2,353            | 6.788             | 58,797      |
| Main Condenser  | 5     | 0.127          | 48.9             | 113.5            | 2,235            | 6.962             | 72,545      |
| MCWP            | 6     | 2.75           | 49.11            | 3.713            | 549              | 1.641             | 956.1       |
| Cooling Tower   | 7     | 2.3            | 31.7             | 5.328            | 523.9            | 1.578             | 819.6       |
| 1st Ejector     | 8     | 6.5            | 48.9             | 0.7947           | 2,232            | 6.77              | 1,542       |
| Motive Steam 1st| 9     | 5.91           | 165.37           | 1.777            | 2,725            | 6.693             | 3,820       |
| Motive Steam 2nd| 10    | 5.91           | 165.37           | 1.758            | 2,725            | 6.693             | 2,343       |
| Int-Cond In     | 11    | 6.5            | 48.9             | 2.572            | 2,137            | 5.302             | 4,747       |
| Int-Cond Out    | 12    | 0.41           | 48.8             | 2.513            | 204.3            | 0.6882            | 219.2       |
| Aft-Cond Out    | 13    | 0.95           | 48.8             | 2.513            | 411.5            | 0.882             | 301.4       |
| 2nd Ejector     | 14    | 6.5            | 40.5             | 0.6617           | 2,172            | 6.343             | 1,244       |
| After-Cond In   | 15    | 6.5            | 40.5             | 2.42             | 2,137            | 5.302             | 4,468       |
| Primary Int-Cond| 16    | 2.97           | 31.54            | 0.04492          | 560.1            | 1.669             | 12.07       |
| Primary Aft-Cond| 17    | 2.97           | 31.54            | 0.04492          | 560.1            | 1.669             | 12.07       |
| Final Ejector   | 18    | 0.78           | 48.8             | 0.07345          | 2,209            | 6.199             | 140.9       |

The 1st ejector and 2nd ejector components have an energy value of 1,542 kW and 1,244 kW that is used to suck non-condensable gas from the main condenser and inter condenser. MCWP component has an energy of 956.1 kW which is used to drain water from the main condenser to the cooling tower for cooling. The cooling tower has an energy amount of 819.6 kW which is used to assist condensation process in the main condenser, inter condenser and after condenser. Generally the energy value from each of the main system components of Kamojang’s Unit 2 geothermal plant shows the amount of energy derived from the cooled output of the steam turbine.
energy lost in each component due to the decreasing in enthalpy that exited on each component during the process when the geothermal plant operates.

6.1. Main System’s Exergy Analysis

The exergy analysis is made to determine the magnitude, location and cause of irreversibility or loss of exergy. In Table 3. It can be seen that the amount of exergy entered into SRH is about 25, 4432 kW and the output exergy is about 254,175 kW. The exergy loss in this component is due to the venting process in the vent structure. In the High Pressure Separator (HPS), it receives incoming exergy and outgoing exergy leaving the separators at 25, 4175 kW and 25, 3404 kW respectively and has an irreversibility of 771 kW. Other component demister is a component that ensures the steam is completely clean and ready to enter the turbine. Exergy input and output of the demister is about 253,404 kW and 237,590 kW and has an irreversibility of 9,309 kW, irreversibility caused by the length of operation time resulting in the rubber pack in the demister to have stiffness and cracks and hence causes the occurrence of steam leakage on that part. It can be seen that the SRH, separator and demister have 99.9%, 99.7% and 96.33% of exergy efficiency where the three components have an exergy efficiency above 95% which means there is not much exergy loss at the components.

Turbine is a vital component of a plant with a value of exergy input and output at about 245,226 kW and 179,545 kW, while turbine irreversibility is at 64,550 kW where 55,000 kW of them are converted into electrical energy. The turbine efficiency is at 73.56%.

| Component                | Exergy In (kW) | Exergy Out (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        | 6,682           | 185,427              | 3.478                 |
| 1st Ejector              | 5,149          | 5,063           | 85.68                | 98.34                 |
| Inter Condenser          | 5,128          | 4,661           | 467.2                | 90.89                 |
| 2nd 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                 |

The exergy efficiency of the main condenser is at 3.478%. Inter condenser and after condenser have an efficiency of 90.89% and 85.47%. 1st ejector and 2nd ejector have an exergy efficiency of 98.34% and 85.47%. Lastly, the cooling tower’s component has an exergy efficiency of 96.91%.

6.2. Grassman Diagram for existing system

Figure 4 shows the grassman diagram for the existing dry-steam plant. The total available exergy is 25, 4432 kW. The exergy loss in the SRH, separator, demister, turbine, main condenser, 1st ejector, inter-condenser, 2nd ejector, after-condenser and the cooling tower at about 257,5 kW (0.10% ), 771 kW (0.303%), 9,309 kW (3.65%), 9,550 kW (3.75%), 185,420 kW (72.87%), 85.68 kW (0.033%), 467.2 kW (0.183%), 139.6 kW (0.054%), 701.9 kW (0.275%) and 166.4 kW (0.065%) respectively and the net power produced is 47,556.72 kW (18.69%).
6.3. Exergy analysis of Binary System

The value of pressure, temperature, enthalpy and entropy as well as the exergy flow in each according to respective state is shown in table 4 as follows.

Table 4. Binary system analysis

| Component          | State | Pressure (bar) | Temperature (°C) | Enthalpy (kJ/kg) | Entropy (kJ/kg.K) | Energy (kW) | Exergy in (kW) | Exergy out (kW) | Irreversibility (kW) | Exergy Efficiency (%) |
|--------------------|-------|----------------|------------------|------------------|-------------------|-------------|----------------|-------------------|-----------------------|-----------------------|
| Binary Turbine     | 1     | 7              | 107.7            | 495.6            | 1.366             | 5,967       | 1,132          | 1,063             | 69.45                 | 93.87                 |
| Binary Turbine     | Isentropic | 1s        |                  |                  |                   |             |                |                   |                       |                       |
| Recuperator Inlet  | 2     | 1.125          | 42.04            | 391.5            | 1.256             | 4,752       | 290.9          | 286.4             | 4.51                  | 98.45                 |
| Air Cooling        | 3     | 1.125          | 39               | 386              | 1.239             | 4,689       | 286.5          | 14.67             | 271.9                 | 5.12                  |
| Condensor          | Outlet| 4              | 1.125            | 39               | 30.81             | 0.1016      | 545.3          |                  |                       |                       |
| Pump               | 5     | 7              | 39.48            | 31.95            | 0.1022            | 556.6       | 30.44          | 28.58             | 1.863                 | 93.88                 |
| Pump               | Isentropic | 5s        |                  |                  |                   |             |                |                   |                       |                       |
| Preheater Inlet    | 6     | 7              | 57.69            | 76.64            | 0.2411            | 1,080       | 1,095          | 1,025             | 69.94                 | 93.61                 |
| Evaporator Inlet   | 7     | 7              | 107.7            | 208.3            | 0.6111            | 2,615       | 24,631         | 13,355            | 11,276                | 54.22                 |

The binary turbine have 5,967 kW of energy which is the actual turbine work, while the ideal work of the turbine is about 5,247 kW. The exergy input and output are 1,132 kW and 1,063 kW. Therefore the irreversibility is 69.45 kW

In the recuperator, it has an exergy input and output of 290.9 kW and 286.4 kW, while the irreversibility is at 4.51 kW. The pumping component has an actual pump work of 558.6 kW and an ideal pump work of 556.6 kW. The efficiency of binary turbine, recuperator, air cooling condenser,
pumps, preheater, and evaporator are 93.87%, 98.45%, 5.12%, 93.88%, 93.61%, and 54.22% respectively. Several components have an exergy efficiency above 93% which means there is not much exergy loss in the component. The smallest exergy efficiency in the water cooling condenser component is about 5.12%.

6.4. Grassman Diagram for binary system
The total exergy entered into the system amounted to 13,002 kW. The exergy loss on the binary turbine, recuperator, air cooling condenser, pumps, preheater and evaporator of 69.45 kW (0.053%), 4.51 kW (0.034%), 271.9 kW (2.09%), 1.863 kW (0.014%), 69.94 kW (0.537%), 11,276 kW (86.72%) respectively. Figure 5 also shows the net power generated is 1,308.337 kW or 10.06% of the total available exergy.

![Grassman Diagram for binary system](image)

**Figure 5.** The grassman diagram for binary

6.5. A combination of performance
Exergy analysis performance shows that the net power output of the combination plant in Kamojang are described in Table 5.

| Parameter               | Dry Steam System | Additional Binary System | Dry Steam-Binary Combination |
|-------------------------|------------------|--------------------------|------------------------------|
| Net power output (kW)   | 47,556.72        | 1,308.337                | 48,865.057                   |
| First law efficiency (%)| 16.45            | 2.99                     | 19.44                        |
| Second law efficiency (%)| 18.69          | 10.06                    | 28.75                        |

In above table, it shows that the main system of dry-steam in Kamojang has a net power output of 47,556.72 kW with the first law and second law efficiency of 16.45% and 18.69% respectively. Furthermore, the additional of binary has a power output of 1,308.337 kW with the first law efficiency and second law efficiency of 2.99% and 10.62%, respectively. Meanwhile in combination, has the net power output 48,865.057 kW. The first law and second law efficiency are 19.44% and 28.75% respectively.
7. Conclusion

Based on the results previously described, it can be concluded as follows:

1. Exergy analysis on the main system of Kamojang’s Unit 2 geothermal plant shows the net power output is about 47,556.72 Kw with the first law efficiency and second law efficiency equal to 16.45% and 18.69% respectively.

2. Exergy analysis on the additional binary system shows the net power output of 1,308.337 kW with the first law efficiency and second law efficiency of 2.99% and 10.62% respectively.

3. There had been an increase in the net power output at about 48,865.057 kW when the primary system and the additional binary systems are combined (Bottoming Binary System in Kamojang’s Unit 2 geothermal plant). There is an increase on the first law efficiency and second law efficiency by 19.44% and 28.75% respectively.

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