Updated Numerical Model of Mataloko Geothermal Field

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Abstract. Data collection and further geoscience studies have been carried out in the Mataloko area at the end of 2019. In general, the results of the study showed significant differences compared to previous studies. Therefore, it is necessary to update the Mataloko geothermal field’s numerical model following the latest studies’ data and analysis. In this research, numerical modeling will be performed using a TOUGH2 V.2 simulator and graphical interface software. The model will be built and validated at the natural state phase. It is expected that the model can complement existing geoscience studies and can be used by developers in planning field development.

1. Introduction

The use of reservoir modeling in geothermal fields’ planning and development has become common practice for 10-15 years ago. More than 100 geothermal fields have been modeled worldwide [1]. Reservoir modeling can be a powerful tool in evaluating field development strategies implemented in geothermal fields. With the increasing use of reservoir simulations, reliable predictions are needed, primarily if associated with high exploration and production risks in a geothermal field [2]. Reservoir parameter conditions have a high degree of uncertainty due to the reservoir’s dynamic nature, especially during the exploitation period. These conditions make reservoir simulations more reliable to use than other approaches, such as volumetric and analytic approaches [3–20]. In this research, a numerical model of the Mataloko geothermal field will be updated based on the latest geoscience data and studies. A simulation will then be carried out on the model built to determine the proven reserve size and the best field development strategy implemented in the Mataloko geothermal field. The study results are expected to be valuable input for PT PLN (Persero) as the Mataloko Geothermal Working Area developer.

There are several reasons why the analysis of the Mataloko geothermal field is needed. First, the electrification ratio of the province of East Nusa Tenggara is the lowest in Indonesia. Second, the government promotes Flores as a geothermal island. Third, Mataloko geothermal power plant had already been in production, although not for a long period, at least this condition proves the existence of Mataloko’s geothermal potential resource.

PT PLN (Persero), as the Mataloko Working Area developer, plans to develop the field by constructing the Mataloko power plant 20 MW in 2022 and 2023 and the re-activation of the 1x2.5 MW PLTP Mataloko (PT PLN, 2019). So, further geoscience studies, which comprise data collection and...
geoscience studies, have been carried out in the Mataloko area from the end of 2019 to early 2020. In general, the result of the study has significant differences compared to previous studies.

Numerical modeling requires detailed information from the integration of geoscience studies and well data described in a conceptual model. Different geosciences analysis will give different results to the numerical modeling conducted. From previous research, the first numerical model in the Mataloko geothermal field has been made. The model is validated to the natural state, and then geothermal reserves are calculated using the heat stored method with a probabilistic approach with Monte Carlo. The model shows that the Mataloko geothermal field is a steam-dominated geothermal system controlled by the Wae Luja fault. Mataloko has a productive area of 4.5 km² in the form of a reservoir of steam dominance at shallow depths and more than 10.2 km² of reservoirs dominated by water at greater depths with a total reservoir depth of 1750 m and temperatures ranging from 210–275°C [17]. If looked more in-depth, the numerical model was compiled based on references until 2018 or before further geoscience studies were conducted in 2019-2020.

Based on the conditions above, in this research, a numerical model of the Mataloko geothermal field will be rebuilt based on the latest geoscience data and studies. It is expected that the model can complement existing geoscience studies and can be used by developers in planning field development.

2. Mataloko Geothermal Field Overview
Mataloko geothermal field is located in Ngada district, Flores Island, East Nusa Tenggara province, Indonesia. The nearest airport is Soa-Bajawa Airport, 1 hour from the Mataloko working area. From Jakarta, the location can be reached by flight from Soekarno-Hatta Airport, Jakarta (CGK) to El Tari International Airport, Kupang (KOE) for about 3 hours, and then continue flight to Soa-Bajawa Airport, Bajawa (BJW) for about 1 hour (Figure 1). The Mataloko geothermal field exploration began with implementing the Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia in March 2002 until the Mataloko power plant could operate in late 2011.
2.1. Geological Studies

Based on regional geological studies, volcanic rocks on the island of Flores can be divided into 3 (three) types, tertiary sediments on the north side of the island, tertiary volcanic sediments & rocks in the middle of the island, and quarterly volcanic rocks dominate in the middle to the south side of the island. Based on the map below, the Mataloko working area is in a quarterly volcanic and alluvium product. It is also in one of 2 cinder cones on Flores island, precisely in the Ratogesa cinder cone [21].

Figure 1. Mataloko working area location [21].
Based on the analysis and direct observation in the field, 5 (five) confirmed structures around the Mataloko working area. The structures are Wae Luja, in the middle and interpreted as permeable; Matawae 1, in the northwest side and interpreted as impermeable faults; Tiwulina 1 and 5, in the southeast side, which is also interpreted to be impermeable; and Taranage, which is also on the southeast side of the Mataloko working area but cannot be interpreted. Figure 2 shows the confirmed structures in the Mataloko area compared with the lineament study.

Based on the manifestations distribution, lithology, and the existence of the faults, the geothermal system in the Mataloko area can be divided into 4 (four), namely the Ratogesa Crater System in the middle of the Mataloko’s working area, Soge System in the northwest side. Both of them separated by the Matawae 1 fault. Then the Razhimere System and the Nage Caldera System. However, based on the availability of data and the confidence level, this study will concentrate only on the Ratogesa Crater System.

2.2. Geochemistry Studies
Based on its appearance, the manifestations distribution in the Mataloko area can be divided into 2 (two) areas, namely the Ratogesa crater, which has very active manifestations, and in the Matawae area where there is a warm spring. The location and properties of each manifestation in Mataloko are shown in Figure 3 and Table 1.
Figure 3. Manifestations distribution’s map [21].

Table 1. Manifestations properties [21].

| Name                  | Location        | Manifestation Type | Ambient Temperature (°C) | Manifestation Temperature (°C) | pH    | TDS (mg/kg) | EH (mV) |
|-----------------------|-----------------|--------------------|--------------------------|--------------------------------|-------|-------------|---------|
| Wae Luja Hot Stream   | Ratogesa Crater | Hot Stream         | 26.1                     | 91                             | 2.92  | 763         | 292.6   |
| Wogoalo Hotpool 1     | Ratogesa Crater | Hot Pool           | 30                       | 55.6                           | 5.80  | 195         | 82.2    |
| Wogoalo Hotpool 2     | Ratogesa Crater | Hot Pool           | 30                       | 94.5                           | 4.00  | 387         | 207     |
| Matawae Warm Spring   | Ratogesa        | Warm Spring        | 30.4                     | 35.3                           | 6.35  | 192         | 50      |
| Wogo Cold Spring 1    | Ratogesa        | Cold Spring        | 21.2                     | 24.9                           | 6.00  | 98          | 58.5    |
| Wogo Cold Spring 2    | Ratogesa        | Cold Spring        | 21.2                     | 25.5                           | 6.00  | 196         | 60.5    |
| Matawae Cold Spring   | Ratogesa        | Cold Spring        | 25.3                     | 31.5                           | 6.50  | 144         | 37      |
| Reko Cold Spring      | Reko            | River              | 30.3                     | 23.4                           | 8.00  | 100         | -40     |
| Soke Cold Spring      | Soge (Wellbore) | Cold Springs       | 28                       | 23.3                           | 6.52  | 120         | 34      |
| Dadawea Cold Spring   | Dadawea         | Cold Springs       | 23.5                     | 18.3                           | 7.00  | 90          | 13      |
| Wae Luja Steam Vent   | Ratogesa Crater | Steam Vent         | 28.7                     | 96                             | 4.70* | -           | -       |
| Wogoalo Steam Vent    | Ratogesa Crater | Steam Vent         | 30                       | 93.3                           | 3.60* | -           | -       |

* pH measurement from condensate.
Based on the Na-K-Mg diagram (Figure 4), both manifestations and well production fluids are at the Mg corner point. This condition interprets that the fluid is meteoric water. Simultaneously, the wells have not reached the reservoir area yet and may still at a depth of caprock or shallower steam-heated aquifers, which are commonly called steam pockets [21]. Based on CO₂/H₂ and Na/K geothermometers, reservoir temperatures in the Ratogesa Crater System is estimated to be 250-280°C.

**Figure 4.** Na-K-Mg diagram [21].

2.3. Geophysical Studies

The magnetotelluric and gravity measurements carried out in 2019 cover the Mataloko working area to the far north. In general, the MT data shows an area with low resistivity (<10 μm) at shallow depth, which is interpreted as a caprock. This condition follows argillic alterations on the surface surrounding the manifestations, and clay alterations are reported almost consistently from the top to the bottom of the wells [21].

3. Static Conceptual model

The integration of the geosciences analysis and well data is then outlined in a conceptual model. Conceptual models provide a comprehensive description of the structure and nature of a geothermal system under review. Conceptual models generally describe the geothermal system’s essential components, including caprock, heat source, fluid flow direction, reservoir, upflow zone, outflow zone, geological settings, and recharge flow. Notice that this research will focus on 1 (one) of the 4 (four) geothermal systems in the Mataloko area, the Ratogesa Crater System because it has the highest confidence level.

The heat source of the Ratogesa Crater System is young magmatic (active volcanic) based on field observations, which shows an abundance of sulfur deposits associated with high-temperature acid manifestation. This interpretation is also supported by geochemistry analysis, which shows the indication of magmatic input from NCG samples in MT-2, MT-3, MT-4, and MT-5, where magmatic gases such as HCl, SO₂, and HF are detected despite having low concentrations. This heat source is interpreted as dyke under the Ratogesa crater [21], as shown in (Figure 5).

Reservoir rocks are interpreted as high permeability tuff and be the primary permeability control in the Ratogesa Crater System. The reservoir temperature is 250-280°C, based on geothermometer CO₂/H₂ and Na/K. For reservoir type, it is interpreted as a two-phase reservoir or liquid dominated reservoir with high temperature. The reservoir boundaries are observed from geological mapping data likes showed with the magenta line in (Figure 5).
As discussed earlier, caprock is interpreted in low resistivity (<10 μm) shown at MT data. The upflow zone of the Ratogesa Geothermal System is located within the crater itself, where the manifestation occurs. The outflow zone is interpreted in the south-west area of Mataloko’s working area, which has a lower elevation. Figure 6 and Figure 7 show the Mataloko geothermal field’s conceptual model based on integrating the latest geoscience studies.

**Figure 5.** Mataloko conceptual model’s top view [21].
4. Mataloko Numerical Model

The construction of the Mataloko numerical model was carried out using the TOUGH2 V.2 simulator with graphical interface software. The building of the reservoir model is carried out in stages[8, 9, 12, 16, 18, 19], as described in the following sub-sections.
4.1. Equation of State (EOS) Selection
One of the features contained in TOUGH2 is the existence of various state equations that can be used to accommodate variations in fluid content in the reservoir (fluid properties) or commonly called the Equation of State (EOS). There are 11 variations of EOS that users can choose from in the TOUGH2 V.2 software [22]. Generally, Mataloko geothermal system involves fluid in the form of water, which is then heated by steam at high temperatures at a deep depth [21]. Based on these conditions in this study, the model was built using variations of the EOS 1 model for water and water with tracers without considering the chemical content and the non-condensable gas (NCG) content.

4.2. Model’s Dimension
In this study, the dimensions of the model are made much broader to allow any future updates. This condition accommodates the estimated existence of 4 (four) geothermal systems located around the Mataloko working area based on the distribution of surface manifestations, structures, and chemical composition of fluids [21]. The model dimension is 10x7.5 km², with orientation 0°. Overlay of the model, the Mataloko working area, the latest geoscience research area, and the geothermal system components are shown in (Figure 8). The model is shown with a red dashed line, while the latest geoscience research area is shown with a blue dashed line. A solid red line marks Mataloko’s working area. The red and brown areas show the estimated heat source and reservoir area in the Ratogesa Crater System. In comparison, the areas with color degradation show the MT and gravity data capture areas.

4.3. Gridding and Layering System
The model was built with 5 (five) main layers, namely atmosphere (ATM), groundwater (GWT), caprock (CPR), reservoir (RSV), and basement (BST) with vertical thickness reaching 2577m, as shown in table 2. The ATM, GWT, and upper side of CPR layers are made according to the field topography to represent actual conditions in the field. The topography is obtained with Global Mapper V.19 software. In contrast, the other layers (RSV and BST) are determined based on the conceptual model. In this study, the model was built using rectangular grid blocks with a variety of dimensions. The smallest dimension of the grid block is 100mx100m, which is used in the reservoir area, while the largest dimension of the grid block is 600mx500m at the side boundary of the model.

Figure 8. Overlay model with other areas.
Table 2. The main layers of the model.

| Layer      | Elevation (masl) | Thickness (m) |
|------------|------------------|---------------|
|            | Top              | Base          |
| Atmosphere | 725 to 1577      | 625 to 1477   | 100           |
| Ground Water| 625 to 1477      | 575 to 11427  | 50            |
| Caprock    | 575 to 11427     | 200           | 93 to 306     |
| Reservoir  | 200              | -600          | 800           |
| Basement   | -600             | -1000         | 400           |

4.4. Material Properties and Configuration

The material’s definition is determined based on the nature and type of rock data such as density, porosity, permeability, heat conductivity, and specific heat of rock, which must be included as properties in each grid block model. Considering that logging material in wells in Mataloko only has a maximum depth of 756.47 m in MT-4 wells, the model uses values commonly applied in geothermal fields in the initial conditions. The reservoir permeability value to be calibrated in natural state resistance has values ranging from 25 mD to 80 mD. The porosity value is set between 1% to 12%, where the high porosity value is the porosity of reservoir rocks, and the low porosity value is the porosity of caprock. The specific density and heat value of rocks is set at the same value of 2600 km/m³ and 1000 J/kg.°C, while the thermal conductivity has values ranging from 2-2.5 W/m°C. Appendix 2 shows the value of model rock properties that have reached natural state conditions.

4.5. Internal Boundary

Internal boundary models are determined based on the presence of structures/faults according to geological studies. These faults were drawn using Google Sketch Up software as input for graphical interface software. The existence of these faults will be beneficial in determining the type of material in the grid block model, both permeable and impermeable. There are 5 (five) main faults in the Mataloko geothermal field, namely Wae Luja, Matawae 1, Tiwulina 1 and 5, and Taranage faults. The Wae Luja fault is permeable, while the Matawae 1, Tiwulina 1, and 5 faults are impermeable. Figure 9 shows faults in the model.
4.6. Initial Condition

The model’s initial conditions are approached using 2 (two) equations: the temperature gradient equation and the pressure gradient as a depth function. It is assumed, a pressure of 1 bar at the ATM layer with a temperature of 25°C, while the highest topography is 1477.23 m. The temperature gradient equation uses the general temperature gradient of a geothermal field that is 3°C/100m. For the pressure gradient equation using the P-T well logging MT-3 well on July 24, 2004, a pressure value of 21.5 bar was obtained at a depth of 562.45 m. Based on these data, the pressure and temperature gradient equation as the initial condition model is obtained:

\[ T_z = 69.317 - 0.03z \]  
\[ P_z = 5.58E6 - 6100z \]

The two equations above show the pressure and temperature values in each grid block model in the initial conditions as a function of depth.

4.7. Boundary Condition

The atmospheric layer of the model is used as the top boundary. All blocks in this layer are considered to have the same properties. The temperature of 25°C and 1 bar pressure are used as initial conditions and set to a fixed state. They are not affected by the reservoir conditions during the simulation until they reach a steady-state condition.

The basement layer is located at the bottom of the model, and it is used as a boundary condition that contains a heat source. The heat source position in the Ratogesa Crater System geothermal system is not right underneath it but instead shifting towards the southeast. Assigning heat source material is done by overlaying the model of views of existing conceptual models. The heat source material is represented by 124 blocks from 33,600 blocks in the model. All blocks in the heat source area in the basement are also set to a fixed state. The heat source’s initial value is set at 110 bar pressure and a temperature of 310°C.

5. Result and Analysis

The natural state condition describes the geothermal field’s condition just before being exploited. The pressure and temperature are in a steady-state (equilibrium) condition that does not change or is relatively constant with time. Some adjustments to the model parameters are needed, including the rock material’s properties, especially the permeabilities, initial pressure, initial temperature, and location and dimensions of the heat source to achieve a natural state condition. Changing and adjusting the parameters of the model is carried out continuously until a natural state is achieved.

The Mataloko geothermal field model is interpreted to have reached a natural state condition, with a running time of more than 5 million years. Figure 10 and Figure 11 show the temperature, heat flow, and mass distribution in the model. It can be seen that there is a deep infiltration from meteoric water to the deeper depth where the recharge area is in the area around the Mataloko WKP, which has a higher elevation. The water is then warmed up by the Heat Source and then rises in the deep reservoir zone dominated by convection heat transfer. Then the mass flow stops at the caprock layer while the heat flow continues through conduction heat transfer. The heat transfer from the heat source passes through the entire rock layer, especially in the reservoir area, to form the isothermal line shown in both images. It can be seen that the isothermal line shows the highest value under the Ratogesa crater area. The result is consistent with initial estimates based on geoscience studies that the Ratogesa Crater is an upflow zone. The temperature at the top of the reservoir reaching values of 242-254°C, lower when compared to the initial interpretation through a static conceptual model where the estimated temperature top of the reservoir is 250-280°C (Figure 12).
Figure 10. Temperature distribution and mass flow vector.

Figure 11. Temperature distribution and heat flow vector.

Figure 12. Temperature top of the reservoir.
The pressure and temperature changing process cause some of the water to change in phase. It forms a steam cap on the upper side of the reservoir, and it continues to the shallow depth through the Wae Luja fault, which has a relatively high permeability. Based on Figure 13, it can be seen that the highest vapour fraction value is on the upper side of the deep depth reservoir zone with the highest fraction value of 0.799. Based on these conditions, it is estimated that the deep reservoir is a 2-phase reservoir.

The result is also consistent with the conceptual model’s initial interpretation that the geothermal system has a 2-phase reservoir and has a steam pocket at shallow depth (PT PLN Gas and Geothermal, 2020).

With the data limitations, the model’s pressure and temperature distribution will be calibrated using the MT-3 well shut-in test data conducted on July 24, 2004. Figure 14 shows the comparison of the P&T model with the previous model and also MT-3 well data. As can be seen, the model’s PT profiles have a pretty good fit with MT-3 well data and much better values than the previous model. Calibration at this stage is also evaluated qualitatively using the root mean square error (RMSE) method. The RMSE in this study shows that the error for temperature is 9.51°C, and for pressure is 1.85 bara (Figure 15).

Based on these two-comparative data, it appears that the model has a much more appropriate P&T value and has a much lower error value when compared to the previous model based on MT-3 well data.

This model gives a better result than the previous model [17], based on P&T matching data. Therefore the research can be continued by doing history matching [10, 11, 18], forecast [4, 5], and financial models [23, 24].

![Figure 13. Steam cap formed on the model.](image-url)
Figure 14. Pressure & Temperature match.

Figure 15. RMSE comparison.
6. Conclusion
The Mataloko geothermal field's numerical model based on the newest geoscience reviews has been successfully reaching its natural state. Based on the P&T matching and RMSE method, the model gives better results compared with the previous model, so it can be concluded that the model can represent the actual field conditions.

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