Updating the Conceptual Model of Lumut Balai Geothermal Field, South Sumatera, Indonesia Using Numerical Simulation

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Abstract. The Lumut Balai geothermal field is classified as a volcanic hydrothermal system characterized by the presence of fumaroles and hot springs. Downhole measurements indicate that this geothermal system has a liquid-dominated reservoir with temperatures of 240-260°C. This study presents a natural state model and updated the conceptual model of Lumut Balai based on published geological, geophysical, geochemical, and well data. The model was validated using available temperature data from three drilled wells. Furthermore, the mass and heat flow through the model were also validated with geoscience and well data. A match to the natural state condition was achieved by adjusting the horizontal and vertical permeability. The updated conceptual model of Lumut Balai geothermal field has been shown to be physically realistic by a numerical model. The model temperatures, mass flow, and heat flow are well-matched with the actual data, although there is still some room for further improvements.

1. Introduction
The Lumut Balai geothermal field is in Muara Enim District, South Sumatera, Indonesia. The field is 274 km from Palembang, the capital of the province of South Sumatera, as shown in Figure 1. Based on the results of geoscience studies and well data, this field is water dominated system with reservoir temperature around 240 – 260°C. Manifestations such as fumaroles and hot springs are controlled by structures. Lumut Balai geothermal field is classified as low enthalpy system due to its reservoir temperature measured by well logging, which range between 220 – 250°C [1], with enthalpy value ranged between 943 kJ/kg – 1100 kJ/kg [2].

The objectives of this study are to test and update the conceptual model of Lumut Balai geothermal field by calibration of a numerical-model based on published geological, geophysical, geochemical, and well data. Temperature, mass and heat flow and fluid condition of the model were calibrated using available data until a well-matched natural state condition was achieved. The natural state modelling was carried out using TOUGH2 [3].

Several studied on numerical simulations have been conducted by researchers in the world. Some of them are natural state model of Ulumbu geothermal field [4], Mataloko geothermal field [5], Kotamobagu geothermal field [6], Olkaria geothermal field [7], Mutnovsky geothermal field [8], Kerinci geothermal field [9] [10], improved natural state simulation of Arjuno-Welirang geothermal field [11], updated on modeling of the Rotokawa geothermal system [12], numerical simulation of Northwest Sabalan geothermal field [13], numerical simulation for two phase liquid dominated geothermal reservoir with steam cap underlying brine reservoir [14], and other geothermal field in the world.
The method used in this study is based on the idea that a numerical simulation of heat and mass flow in porous media (i.e. a TOUGH2 model) will provide a physically realistic representation of the system. A conceptual model based on this can therefore also be considered to be a physically possible representation. Hence the result of numerical simulations can be used for updating the conceptual model of a geothermal system. Some conceptual models of geothermal fields that have been updated use this method include Ciwidey-Patuha geothermal field [15], Cisolok-Cisukarame geothermal field [16], Atadei geothermal field [17].

2. Conceptual Model Review

Conceptual models are a descriptive and qualitative model which provides a full description of the structure and nature of the system in question [18]. The initial conceptual model of Lumut Balai geothermal field is shown in Figure 2. The model shows a heat source beneath Bt. Lumut area with a large reservoir within the caldera rim. This model should be updated due to the following reason. The wells temperature indicate the presence of more than one heat source. Thin can be known from the temperature of well LMB A-2 (the farthest well from heat source as describe in the model) which higher than well LMB 1-3. Moreover, production tests shows well LMB A produce steam average of 10-14 MW, while LMB 2, even production tests has not been performed, vertical production test shows very less steam flowrate [1]. Hence, there is a possibility that this field has more than one compartments of reservoir. This model will be verified and improved by the numerical model.

2.1. Geological review

Lumut Balai field is part of the Bukit Barisan zone, characterized by the presence of 50 centres of Quaternary volcanic activity along the Sumatra Fault [1]. Geographically, Lumut Balai is located about 2 km northeast of Sumatra Fault. Figure 3 shows the geological map of Lumut Balai area.

Geologically, Lumut Balai is dominated by Quaternary age volcanic rocks, above the Tertiary basement composed of sedimentary rocks. The 1.8 Ma basement rocks can be seen in the NE of the prospect area, and consist of shales and sandstones, and several lithologies contain Ignite. The youngest rocks are found at Lumut Dome which is estimated to be 0.64 Ma and is interpreted to be the heat source for Lumut Balai. This rock consists of andesite flows and pyroclastics. A volcanic stratigraphy study shows indications of heat source within the caldera and centered in several locations which are likely to
be intrusions. This can be seen from hummocks within the caldera, usually formed by the intrusion. The heat source is thus a cooling magma in as the presence of the quaternary rocks.

![Initial conceptual model of Lumut Balai geothermal field](image)

**Figure 2.** Initial conceptual model of Lumut Balai geothermal field [19].

The distribution of thermal manifestations within the caldera is shown in Figure 3. Some manifestations within the caldera are be associated with a North-South structure, and some others appear to be associated with SW-NE and NW-SE structures.
2.2. Geochemical review
A geochemical study was done by surface manifestations, which are hot springs and fumaroles, mostly within the caldera, with some outside. This indicated upflow and outflow zones using Cl-SO\textsubscript{4}-HCO\textsubscript{3} ternary diagram, as shown in Figure 4a. There are two upflow areas: Lumut Dome and Gemurah Besar area, shown by sulfate water manifestation indicating boiling over the hot upflow. These two upflow zones indicates that the reservoir within the caldera has two compartments, one in Lumut Dome (L. Dome) area, and the rest in Gemurah Besar (G. Besar) area. Bicarbonate water indicates an outflow zone.

The temperature of the Lumut Balai reservoir is deducted from geothermometer calculations using samples from liquid water manifestations. Based on Na-K-Mg geothermometer, as shown in Figure 4b, the thermal manifestations in G. Sidawan and Gemurah Besar Kelumpang are in partial equilibrium conditions, which indicates that the fluids come from the reservoir directly, while the other manifestations are in immature water which indicates that the fluid has been mixed with groundwater and reacted with rock. The reservoir temperature based on Na-K-Mg diagram is estimated to be around 240-260°C.

2.3. Geophysical review
Gravity and magnetotelluric data were used in this study. Figure 5 shows a residual Bouguer anomaly map of the Lumut Balai geothermal field [18]. High anomaly value indicate greater rock density, while the lower anomaly, below 0 mGal, denotes a geological fault and caldera rim. The area within the higher
density anomaly can be seen in Lumut Dome area which extends to Gemurah Besar area. The interpretation is that these are igneous rocks which signify heat source of Lumut Balai geothermal Field.

Figure 4. (a) Cl-SO4-HCO3 diagram of Lumut Balai manifestation fluid; (b) Na-K-Mg geothermometer (after [19]).

Figure 6 shows the resistivity anomaly map of Lumut Balai geothermal area. The area with low resistivity value, lower than 10 ohm.m, indicates a caprock area. It can be interpreted that the low resistivity area is dominant at elevation -500 to 1500 masl and the reservoir is beneath the caprock. The area of the reservoir was estimated to be around 26 km$^2$.

2.4. Well data
More than 20 wells were drilled (from different well pads) up to 2017 [1], as shown in Figure 7. Due to data limitations, this research uses three wells, namely LMB 1-3, LMB A-2, and LMB 2-1 [20]. All these wells reach a temperature higher than 240°C. The temperature and pressure profile of LMB A-2, LMB 1-3, and LMB 2-1 are a result of 339 days, 194 days, and 60 days of heating, respectively.
2.5. Implications for the conceptual model
While the geological study has heat source beneath Lumut Dome area, the volcanic stratigraphy study indicates heat sources distributed within the caldera, which are likely to be intrusions. Geochemistry shows that the reservoir within the caldera has two compartments, due to their own upflow and outflow zone, which is Lumut Dome area and Gemurah Besar area. The geophysical interpretation is of a heat
source that extends from Lumut Dome area to Gemurah Besar area. Furthermore, LMB A-2 and LMB 1-3, located in Gemurah Besar area, and LMB 2-1, located in Lumut Dome area, have the same pressure gradient. From this we interpret that Lumut Dome and Gemurah Besar area have the same heat source at depth. However, based on an integration of geological, geochemical, geophysical, and well data, the Lumut Balai geothermal system within the caldera is a system with two reservoirs separated by an impermeable structure between Gemurah Besar area and Lumut Dome area. The heat source in this system is a single unit of rock at an unknown depth but appears at a shallower depth as separate intrusions in Lumut Dome and Gemurah Besar area. We will test this with a numerical model.

Figure 7. Location of wells on Lumut Balai geothermal Field (after [1]).

3. Natural State Model

3.1. Model Description
The model was built using TOUGH2 software and the fluid used in the model assumed to be pure water. EOS1 was chosen for the equation of state. It has 19 x 10 km with reservoir area around 26 km². The vertical extent of this model is 4090 m due to the highest topographic and the lowest elevation of the model at -2000 m below sea level and divided into 5 layers. The mesh-type rectangular and a distributed parameter approach is used. The mesh is refined (200 x 200 m) in the reservoir area that is known to have a high temperature and good permeability. The total number of blocks in the model is 32,946. The grid area set in the model is shown in Figure 8.

The characteristic data that represents the geothermal system such as a heat and water source, boundary conditions, and internal permeability structure have been assigned in the computer model and set to reach natural state condition. In the natural state the mass and heat flows in the model are stable. The properties of the rocks that represent geological conditions in the model are shown in Table 1. The
hydraulic and thermal properties are assigned to each block in the computer model, as shown on a cross-section in Figure 9. A tight permeability is used outside the reservoir boundary and higher permeability assigned to grid blocks in the productive area.

The magnitude of the pressure, temperature, water saturation in each block, and the mass flow rate from one block to other blocks for a range of time is calculated by the simulator. Thus, the result of the calculation can illustrate the pressure and temperature gradients, including pressure and temperature versus depth, at all locations in the system.

Boundary conditions are one of the most important matters to be decided in setting up a model of a geothermal system. The following initial and boundary condition were defined to simulate the reservoir system. The top boundary is set to a constant atmospheric pressure and temperature [21]. This study used 25°C and 1 bar with large volume atmospheric block (10^32 m³) to keep the initial boundary condition constant. The side boundary is assumed to be a no flow boundary. The bottom boundaries has a heat input (a positive heat flow into the model) but no mass flow across the boundary.

Figure 8. Gridding area.

Figure 9. Rock properties distribution (right).
Two heat sources were specified in this model in accordance with the geological, geochemical, geophysical, and well data. One heat source is in Lumut Dome area, and one in Gemurah Besar; for both the heat input was distributed over several grid blocks. Different temperature and pressure were specified for each heat source were set; 250°C and 200 bara for Lumut Dome and 290°C and 190 bara for Gemurah Besar. The locations of these heat source were initially based on conceptual data, but during the calibration process were adjusted to achieve the best model output to corresponds to the actual data.

3.2. Modeling Result

The main objective of the natural state calibration is to achieve a model pressure and temperature distribution, and heat and mass flow that matches the observed data. Several parameters need to be adjusted over many model runs (calibrated) until the output matches observation data from three wells.

The result of the simulations successfully reflects the real condition after more than hundreds of iteration of simulation running, adjusting permeability values and location of heat source. As stated before, the locations of heat source were adjusted to achieve the best model output which corresponds to the actual data. The numerical simulation was run until steady-state condition with the simulated timestep was greater $10^{14}$ seconds, meaning that heat and mass flows were stable. Table 1 shows the final permeability values for the model.

| Material | Explanation | $k_{xy}$ (mD) | $k_z$ (mD) | Color |
|----------|-------------|---------------|------------|-------|
| GW       | Groundwater | 0.05          | 0.05       |       |
| CAPR     | Caprock     | 0.0008        | 0.0004     |       |
| CAPR2    |             | 0.8           | 0.8        |       |
| HEAT     | Model Base  | 100           | 100        |       |
| BASE     |             | 0.0008        | 0.0008     |       |
| RES1     |             | 10            | 10         |       |
| RES2     |             | 15            | 7.5        |       |
| RES3     |             | 55            | 27.5       |       |
| RES4     |             | 8             | 4          |       |
| RES5     | Reservoir   | 25            | 12.5       |       |
| RES6     |             | 0.4           | 0.4        |       |
| RES7     |             | 1             | 0.5        |       |
| RES8     |             | 40            | 20         |       |
| RESD1    |             | 40            | 20         |       |
| SIDE     | Boundary    | 0.05          | 0.025      |       |
| FAULT    | Fault       | 0.0001        | 0.0001     |       |
| FAUL2    |             | 170           | 170        |       |

Model mass flow is shown in Figure 10a over a vertical slice CD and Figure 10b over a vertical slice AB. It shows a good agreement between the model and the geoscience interpretation in terms of mass flow as indicated by the direction of fluid flow as well as the location of upflow and outflow on the model. Figure 11 shows the isothermal profile generated by the numerical model. It confirms that the geochemical study in terms of reservoir compartments is physically valid. Well data were obtained from
the shut-in temperature of LMB 1-3, LMB 2-1, and LMB A-2. The pressure and temperature well profile at natural state, and the observation data are shown in Figure 12. There is a good match between model output and the measured well data.

![Figure 10](image)

**Figure 10.** Model mass flow profile over a vertical slice CD (a) and vertical slice AB (b).

The condition of reservoir fluid is evaluated by analyzing the pressure and temperature profile of each well. The presence of small size of steam zone in a liquid dominated reservoir was successfully achieved in the model with a maximum steam saturation of 0.047. In the field data this was indicated by the slope change of pressure at an average elevation of 400 masl in LMB 1-3. The presence of the steam zone in the numerical model shown in Figure 13. This value indicates that Lumut Balai geothermal field is liquid dominated system. As a comparison with other two-phase geothermal field, the result of reservoir simulation in Pratama and Saptadji [14] has steam saturation up to 0.8, a model of Ulumbu [4] 0.65, and a model of Ciwidey-Patuha [5] 0.65.

4. Updated Conceptual Model
Integration of geological, geochemical, geophysical, and wells data are compiled in a numerical model, resulting in an updated conceptual model. There is an impermeable structure separating the Lumut Dome and the Gemurah Besar areas. Compartmentalization of the reservoir in the numerical model is validated pressure and temperature profile from LMB 1-3, LMB 2-1, and LMB A-2. The heat source in this system is conductive heat flow from intrusions in both areas. Figure 14 shows the updated conceptual model of Lumut Balai geothermal field based on the integrated result of numerical simulation and geological, geochemical, geophysical study and three wells data.

![Figure 11](image)

**Figure 11.** Model isothermal profile.
Figure 12. Matching pressure and temperature data between computer model and actual data.

Figure 13. The presence of steam zone resulted from the computer model.
Figure 14. Updated conceptual model of Lumut Balai geothermal field.

5. Conclusion
The natural state model of Lumut Balai geothermal field was successfully developed. It shows a good match with observed data after adding an impermeable structure separating the Lumut Dome and the Gemurah Besar areas and adjusting the heat source locations. The model was calibrated using the temperature and pressure profiles obtained from three exploration wells and guided by geosciences data and interpretation. Updated conceptual model of Lumut Balai geothermal field has been proposed using a numerical model based on geological, geochemical, geophysical, and wells data.

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