Reservoir simulation of Ulumbu geothermal field using TOUGH2 and ITOUGH2 simulator

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Abstract. Ulumbu geothermal field is classified as a natural two-phase geothermal system, located in the south of Mandosawu - Ranakah Old volcanics and Pocoleok, Flores Island. This field produces 4 x 2.5 MW electric power in 2014 until now with temperature between 230–240 °C. This study aims to perform reservoir simulation in the Ulumbu field. The reservoir simulation method aims to determine the reservoir characteristics of the geothermal field. This research used TOUGH2 and ITOUGH2 simulator to simulate the reservoir. The work concept from TOUGH2 is forward modeling while ITOUGH2 simulator to simulate the reservoir. The output of this research is natural state model validated by three wells of the actual measurement (pressure and temperature) and heat flow from the conceptual model. A pressure and temperature profiles are very representative with the data in the three wells. The reservoir location is between Poco Leok and Poco Rii (upflow zone) and continues to the southwest (outflow zone) with an average area of 10.5 km². The top reservoir is at an elevation of 500 m, while the depth is up to -2000 m. Reservoir rock has a permeability value of around 10⁻¹⁴–10⁻¹⁵ m², porosity value of 8–10 %, density value of 2500 kg/m³, and specific heat capacity value of 900 J/kgK. Temperature distribution results of the natural state model show the hydrogeological profile of the Ulumbu geothermal system. The natural state model is then used to help undertake a geothermal field development scenario, that is, to calculate resource reserves and to make recommendations for subsequent drilling zones.

Keywords: Ulumbu, conceptual model, natural state, reservoir simulation

1. Introduction
In general, the purpose of modeling in the geothermal field consists of two things. First, to obtain information about the reservoir system of a geothermal field, which includes physical parameters such as: permeability, dispersivity, and mass recovery. Second, to obtain predictions regarding the response of geothermal reservoir systems to geothermal steam or fluid production in the future, so that various geothermal field management scenarios can be carried out to achieve optimal result [1].

One of the advantages of making a simulation is its calculation in accordance with the laws of physics and mathematics, which is logical and consistent. However, the simulation process is not as simple as entering data then getting results. Often in conducting simulations there are some data that is inconsistent or very difficult to match so that it needs to be carried out a continuous experiment. This shows that it is necessary to check one data against other data, whether it is wrong in its interpretation or conceptual model that must be revised [2].
Ulumbu Geothermal field (figure 1) [3] located in the south of the Old Volcanics of Mandosawu-Ranakah and Pocoleok, which is geographical position on Longitude -8°24.26' and Latitude 120°27.45'. The preliminary scientific studies of Ulumbu prospect were carried out by the VSI, PERTAMINA, AND PLN from 1969 to 1980’s. the area known by high temperature geothermal discharges, such as fields of fumarole and hot springs. The end of 1980’s to early of 1992, the KRTA carried out a feasibility study and planning for exploration drilling [4]. Ulumbu geothermal field was reported to be the brightest chance on the area of Flores having around 100 MWth discharge from this field [4].

This study aims to create a numerical model from Ulumbu geothermal field and then determine the best estimation natural state model by validating pressure and temperature data from the three wells.

2. Geoscientific review

A conceptual model is a pithy visual and verbal explanation of the reservoir that associates the compatible structures and processes that establish its presence and feedback to exploitation [2]. A good conceptual model is created by integrating all geoscientific data such as geology, geochemistry, geophysics and well data [5]. There are some reviews of geosciences and wells data from Ulumbu geothermal field.

2.1. Geological review

Regionally, geology of Western Flores can be divided into two parts, sedimentary and volcanic rocks. Volcanic rocks are divided into two types, tertiary volcanic (north side) and quaternary volcanic (south side). Quaternary volcanic rocks are divided into volcanic (pleistocene) and young volcanic units. Quaternary volcanic rocks are in the upper tertiary volcanic in almost half of the Flores island region. These two types of volcanic rocks are the result of eruptions from several mountains on the Flores island.

Some eruption complexes that control volcanostratigraphy of the Ulumbu area and its surroundings are (figure 2) [3]:
- Rii volcanic complex
- Mandasawu and Ranakah volcanic complexes
- Likong volcanic complex

Indications of the existence of a geothermal system in the Ulumbu area can be seen in the presence of several surface manifestations such as hot spring and fumarole. In addition, alteration was found in several places. Manifestations and alterations that appear on the surface indicate that in the Ulumbu area there is a potential heat source that can be utilized.
Based on regional and field geological data, the kind of rocks in the prospect area are generally volcanic rocks such as andesitic lava, volcanic breccia, lapilli and tuff, where the oldest rocks estimated being a basement rock is Kiro Formation, which is generally dominated by volcanic rocks consisting of lava, breccia and tuff and limestone.

According to Martasari [3], geological structure that works in Ulumbu area is controlled by tectonic and volcanic activity. Normal faults in the north affect to the evolutionary process of the magma movement, which is relative to the northeast. This is supported by the existence of Anak Ranakah active volcano. The appearance of activity hydrothermal alterations, hot springs, and fumaroles related to existence some faults. This indicates a good permeable zone in this area. Mt. Likong is seen growing on a caldera from Mt. Rii where the western flank opened due to collapse and then Mt. Likong grew up. The Northeast – Southwest (direction) fault also expected to be the direction of magma movement. This presumption was strengthened by seeing the development of volcanic activity, starting from the formation of the Mandasawu complex, Ranakah, Likong to Anak Ranakah volcano which currently still shows its activities. In addition, there are two paired structures, estimated to be normal faults, which are located in the southwest of MT. Likong (figure 3) [6].

2.2. Geochemical review
Surface manifestations around the Ulumbu area are hot springs and fumaroles. The hot springs taken were 9 samples and 1 sample taken from the exploration well. While the gas samples taken were 4 samples, 3 samples from wells and 1 sample from fumarole. Hot spring of this area is divided into two groups, sulfate waters and bicarbonate waters types. Hot springs belonging to the sulfate waters are characterized by high content of sulfate (SO\textsubscript{4}), derived from H\textsubscript{2}S oxidation in the vadose zone. While other types of hot springs have high HCO\textsubscript{3} content. This high HCO\textsubscript{3} content is indicated by shallow groundwater which is heated by fluid where the fluid comes from below to the surface which is rich in CO\textsubscript{2} gas content. Two types of hot springs are shown in the SO\textsubscript{4}-Cl-HCO\textsubscript{3} ternary diagram (figure 4a). Based on this diagram, distribution of hot springs is indeed at the SO\textsubscript{4} and HCO\textsubscript{3} angle. Other information obtained in this diagram shows that none of the manifestations in the Ulumbu area are included in the category of mature waters. This means that there is no fluid in the manifestation that comes from the reservoir geothermal activity. Hot springs which have a relatively high percentage of SO\textsubscript{4} and Cl content indicate that the hot springs are in the upflow zone. Whereas other hot springs that have a high percentage of HCO\textsubscript{3} content indicate that the area is the outflow zone.

Figure 2. Volcanostratigraphy map from Ulumbu area
Na-K-Mg ternary diagram analysis (figure 4b) is applied to show the solubility and equilibrium levels of the chemical content of fluid in the Ulumbu area. The result is that all hot springs are in an immature water condition. This indicates that in each of these hot springs has been diluted by meteoric water. In other words, estimation of reservoir temperature, as a result from fluid chemical analysis, is not representative. However, a reservoir temperature is obtained using a gas geothermometer. H₂S/H₂ gas geothermometer analysis shows the average value of reservoir temperature on the Ulumbu geothermal field is 239 °C. At present, well temperature data shows the ± 230 °C.

![Geological structure map in Ulumbu area (modified from [6])](image1)

**Figure 3.** Geological structure map in Ulumbu area (modified from [6])

![SO₄-Cl-HCO₃ ternary diagram, (b) Na-K-Mg ternary diagram](image2)

**Figure 4.** (a) SO₄-Cl-HCO₃ ternary diagram, (b) Na-K-Mg ternary diagram
FT-HSH curve analysis was used to obtain information about the comparison of liquid and vapor saturation values from reservoir fluid. This analysis is useful for determining whether the reservoir system belongs to the category of liquid dominated, vapor dominated, or natural two-phase system. Table 1 shows the $S_V$ and $S_L$ ratio of the three data is around 3:1. While one data shows same ratio ($S_V \approx S_L$). According to Nasution et al. [7], Ulumbu geothermal field is vapor dominated system. However, one sample data shows the different result from the others. It is possible that in the Ulumbu geothermal field there is a zone that has a natural two-phase system.

### 2.3. Geophysical review

Identification of the existence of a geothermal system in the Ulumbu area is indicated by the results of 3-D inversion of MT data. Conductive layer which is a characteristic of the system geothermal as the result of hydrothermal alteration processes appear in the 3-D inversion model. This can be seen in the resistivity cross section of Line 1 (Southwest-Northeast) and Line 2 (North-South). Figure 5 shows the results of 3-D inversion of MT data on Line 1. The clay cap layer is shown by a yellowish red zone. This layer has a resistivity value between 1-11 ohm-meters with a thickness that varies around 200 m at the updome section and around 500 m at the edges even low resistivity in the southwest is thicker than the northeast. At the top of the updome shape, there are several surface manifestations such as fumarole and sulphate hot spring. This shows that the upflow zone of the Ulumbu geothermal system is indeed in the area. In addition to the conductive layer (clay cap), high resistivity anomalies also found in the resistivity cross section. On Line 1, a high resistivity anomaly can be seen appearing in the middle of the section, which is at the bottom of Poco Leok and Poco Rii Mountain.

Meanwhile, the low resistivity anomaly on Line 2 (figure 5b) appears clearer than on Line 1. Updome shape can be seen below the top of Mt. Likong where the manifestations (fumarole and hot springs) and three well appear. Low resistivity zone in the south is thicker than the northern part. These data confirm that the upflow zone in Ulumbu area is in the north - northeast, not in the south - southwest.

The results of the 3-D MT inversion are then compared with other geophysical data, gravity data. Because of limitations of data, this paper only compares it with the curve of residual gravity (figure 6) [7]. Figure 6 shows updome shape in the MT model having a high residual gravity value. This can be seen in the high-rise graph which is relatively match in the form of updome shape in the MT model. This shows that there is a match between 3-D inversion MT model and gravity data on the Ulumbu geothermal field.

### 2.4. Wells data review

Rocks stratigraphy on subsurface that was successfully obtained from the analysis of well data is shown in Table 2. Based on that table, it could be seen that the reservoir layer consists of quaternary volcanic rocks (upper part) and sedimentary rocks (lower part). This is according to geological studies in the previous discussion. Hochstein has classified the type of permeability based on its value into three parts [8]:

- Low permeability: $< 1–3$ mD
- Moderate permeability: $3–10$ mD
- High permeability: $>10$ mD

| Data | $\text{H}_2\text{O}/\text{Steam}$ | $\text{CO}_2/\text{H}_2\text{O}$ | T | $S_V$ | $S_L$ |
|------|-------------------------------|-----------------|---|------|------|
| ULB-1 | 1190.0                        | 3.3             | 197 | 0.45 | 0.55 |
| ULB-2 | 1683.2                        | 14.8            | 257 | 0.78 | 0.22 |
| ULB-3 | 2421.2                        | 13.2            | 268 | 0.71 | 0.29 |
| ULB F | 360.7                         | 1.4             | 276 | 0.69 | 0.31 |
High permeability is found in the lower quaternary volcanic rocks dominated by types of volcanic breccia, andesite, basalt and andesite lava rock. Moderate permeability is spread on tertiary sedimentary rocks and quaternary volcanic rock units. While low permeability relatively dominant in sedimentary rock units.

Kasbani [9] also examined the types of minerals that found in each Ulumbu wells. In ULB-01, these two minerals (epidote and adularia) appear at ± 500 m depth. Its presence appears to the bottom of the well (± 1800 m depth). The existence of the illite clay is also at a depth of ± 500 m depth, where at that depth the well temperature value is around 200 °C. From this information, the top of reservoir zone is at ± 500 m depth. In ULB-02, epidote and adularia was found at a depth of 400–500 m depth. At that depth also found illite clay with well temperature values of ± 200 °C. In ULB-03, epidote was found at 650 m depth. Beside adularia was found at 350 m depth. Although the temperature value of 200 °C already exists at 350 m depth.
2.5. Conceptual model
The conceptual model of the Ulumbu geothermal field has been successfully made based on the interpretation of various kinds of data including geological data, geochemical data, geophysical data, and well data. Figure 7 shows some information about the Ulumbu field geothermal system. Clay cap zone is marked with a yellow layer where the layer has been altered into argilitic rock due to the hydrothermal process from the subsurface which causes this layer to be impermeable zone. The
thickness of this layer reaches 200 meters (400 to 200 meter) in the updome and 500 meters at the edges (400 to -100 m). Reservoir layer thickness is around 1300 to 2000 meters. The layer that becomes the basement of the Ulumbu geothermal system is Kiro sedimentary rock formations based on geological data. Upflow zone is indicated by the presence of fumarole and sulphate hot spring manifestations that located near the top of the Mt. Likong. Outflow zone is indicated to be in the west-southwest of the Mt. Likong where there is a lot of bicarbonate spring which indeed shows high HCO₃ content. The results of gas geothermometer analysis and well data show that the average temperature of reservoir in Ulumbu area is 230 °C.

3. Reservoir simulation
This research used TOUGH2 and ITOUGH2 simulator to simulate the reservoir. TOUGH2 is a algorithmic simulator for non-isothermal flows of multicomponent, multiphase fluids in one, two, and three-dimensional porous and fractured media [9]. The work concept from TOUGH2 is forward modeling while ITOUGH2 is inverse modeling. The first step to create a numerical model is defining the geometry model, layering the model, area focused, initial conditions of the reservoir, and the distribution of physical properties of rocks. The next step is to make a grid. A simulation flowchart used in this study is explained simply and comprehensively through figure 8.

3.1. TOUGH2 modeling
A conceptual model that has been made will be a guide in making numerical or computer model. The process of building this numerical model is assisted by using Petrasim software. The author using TOUGH2-EOS1 for making a numerical model because of the limit of data and to simplify the modeling process. The algorithmic model involves an entire area about 196 km², from 212000 to 226000 E and 9030000 to 9042000 N. The highest elevation attains 2000 m.a.s.l and the lowest elevation of the model was applied to -2500 m below sea level. The size of the grid block alters from the smallest 250 x 250 m to the largest 1000 x 1000 m. The grid is shown in figure 9.

Then the model is divided into 8 layers. Next step is to input physical rock properties and their distribution on the model. Because of limited subsurface data, physical rock properties acquired from trial and error attempts, it was continuously fine-tuned to reach the best result which coincides to the real data. Table 2 shows the list of calibrated physical rock properties in model.

Meanwhile, distribution of rock material can be estimated based on geophysical data and surface manifestations around the geothermal field. Figure 10 show two from eight layer that have been inputted with the distribution of rock/material.

Next step, the author inputs the grid source to supply the mass and energy (heat) of the water fluid to simulate natural-state conditions. There are two kinds of source, meteoric recharge source and heat & mass source. Naturally, overall these two types of sources have different input specifications. Meteoric recharge source from the northeast and south of the caldera has a water mass flow rate with a range of 0.5 kg/s. While the heat source has a flow rate with a range of 2 kg/s. For specific enthalpy values, heat source has a range of specific enthalpy from 1500 kJ/kg to 2000 kJ/kg and meteoric recharge source has a specific enthalpy with a range of 500 kJ/kg. Last step is input an initial condition. Author defines the initial condition of the geothermal system in the reservoir model as a single-phase water at a thermodynamic temperature of 25 °C and a pressure of 1 atm (1,013 × 10⁵ Pa). After all stages have been carried out, Petrasim software can be run and after finish, Petrasim software will produce an output. This output can be visualised into a 3D model (figure 11).

3.2. ITOUGH2 modelling
Next process that was carried out in this study was to do inversion modelling on TOUGH2 model or known as ITOUGH2. ITOUGH2 is a software that brings the ability of inverse modelling for the coding of TOUGH2 [10]. This stage can only be done if forward model has been done first. This is because the input data is the TOUGH2 forward model itself. Generally, ITOUGH2 process is the process of
adjusting the values of physical parameters (porosity, permeability, source and sinks, initial condition, etc.) from the forward TOUGH2 model to provide an output (in this case the temperature and pressure curve) which corresponds to well (real) data.

Before running the ITOUGH2 program, there are several files that must be prepared in various formats, such as TOUGH2 output (t2.file), run_t2.file, inversion input file (it2.file), calibration data (well.dat), and it2_1.exe (executable file from ITOUGH2). If all files are ready, the running process of ITOUGH2 program can begin and will stop automatically when the convergence criteria have been reached. ITOUGH2 output file shows the results of adjusting rock parameters based on matching the well temperature with the model temperature at each iteration. This output will be stored in it2.out file with a long format. The most important part is resume where it is located at the bottom of the file. This resume contains information about the previous estimate value and the best estimate of the rock parameters value.

Figure 8. Simulation flowchart

Figure 9. Numerical model grid
Table 2. List of physical rock properties

| Rock material | Density (kg/m³) | Porosity | Permeability | Heat conductivity (W/mK) | Specific heat (J/kgK) |
|---------------|----------------|----------|--------------|--------------------------|----------------------|
| atmos         | 1              | 0.99     | 1.00E-14     | 1.00E-14                 | 2.5                  |
| land          | 2500           | 0.1      | 6.00E-16     | 6.00E-16                 | 1                    |
| clay          | 2550           | 0.04     | 3.50E-18     | 3.50E-18                 | 2.2                  |
| res 1         | 2300           | 0.05     | 1.00E-12     | 1.00E-12                 | 1.3                  |
| res 2         | 2300           | 0.08     | 1.50E-12     | 1.50E-12                 | 1.3                  |
| res 3         | 2300           | 0.1      | 3.00E-12     | 3.00E-12                 | 1.3                  |
| heat          | 2500           | 0.6      | 1.00E-09     | 1.00E-09                 | 0.5                  |
| rock1         | 2500           | 0.05     | 1.00E-16     | 1.00E-16                 | 2                    |
| rock 2        | 2500           | 0.05     | 3.00E-16     | 3.00E-16                 | 2                    |
| kakle         | 2500           | 0.05     | 1.00E-18     | 1.00E-18                 | 0.8                  |

Figure 10. Distribution of rock material in layer 5 and layer 6

Figure 11. Output from 3D reservoir model (temperature)
4. Results and discussion
Calibration process of temperature data vs. elevation curve of three wells in the Ulumbu field is done by trial and error on two variables, (1) location and intensity (specific rate and enthalpy) of the source and (2) the distribution of rock/material in each grid layer.

4.1. Pressure and temperature matching
In ULB-01 well, the temperature curve between well data and simulation model (TOUGH2 and iTOUGH2) relatively very good match. One part that is relatively less matched is at an elevation of 50 m.a.s.l to -50 m.a.s.l (figure 12). This section is supposed to be a steam cap zone, where there is hot steam which has a higher temperature value than the liquid form. Generally, heat conduction occurs from the surface of the well to 50 m.a.s.l. This can be seen from the high temperature gradient profile, where heat flows through a very conductive layer. This zone is a clay cap (cap rock) layer that does have

![Figure 12. Pressure and temperature matching results](image-url)
very conductive characteristics. Whereas the zone undergoing convection process is at the bottom, seen from a small temperature gradient profile. This zone is reservoir layer. The temperature profile of the model shows a relatively good match with real data (ULB-02 well), except in the 160 m.a.s.l to 0 m.a.s.l where there is a significant difference in the temperature value. Convective zone in this well starts at 164 m.a.s.l. Temperature profiles that decrease at -74 m.a.s.l may not be caused by meteoric fluid flow, but because the rock has a poor permeability. Uniquely, the temperature value in the area is still relatively high, which is around 230 °C. At present, ULB-02 is the main production well to supply for power plants in the Ulumbu field.

Temperature profile of ULB-03 is similar as the ULB-01, but its depth is shallower than ULB-01. The temperature value is also relatively lower than ULB-01. This is suitable with the conceptual model interpretation where the position of ULB-03 is at the edge of reservoir so that the distance is relatively farther from the heat source position. From three wells, ULB-03 is the most difficult to calibrate. This can be seen from the temperature curve that is not match with well data but curve trends are still suitable. Convective zone in this well is at ± 70 m.a.s.l. While at 200 m.a.s.l, temperature profile from the model is not suitable with the well data. The most influential factor is that rock conditions at high elevations are more heterogeneous so that more complex models are needed to produce suitable curve trends.

4.2. Heat and fluid flow profiles

After calibrating, next step is comparing whether the heat and fluid flow profiles in the reservoir are suitable with the conceptual model. Theoretically, fluid flow will stop when it encounters impermeable rocks, such as clay cap and limiting rock (very small permeability) located at the edge of the geothermal system. However, heat still flow to impermeable rock or very small permeability through conduction process. Figure 13 shows heat flow vertically from natural state model. When compared with the conceptual model (figure 7), there is a match between these two models. Upflow zone is indicated by a red zone that shows the high temperature value in the area. High temperature values come from heat source rocks that are below it and then flow to the top. After that, the fluid or heat flows to the west/southwest section from the geothermal system. This is indicated by the area that changes color from yellow to light blue to dark blue (trending to the west). In addition, temperature distribution also seems to have similarities with the conceptual model. In other words, the natural state model that has been made successfully reflects the conceptual model of the Ulumbu geothermal field.
5. Conclusion
Numerical models (natural state) and conceptual models of the Ulumbu geothermal field have been successfully made well, this is indicated by the results of good curve matching between well data and models. The reservoir location is between Poco Leok and Poco Rii (upflow zone) and continues to the southwest (outflow zone) with an average area of 10.5 km². The top reservoir is at an elevation of 500 m, while the depth is up to -2000 m. Reservoir rock has a permeability value of around $10^{-14}$–$10^{-15}$ m², porosity value of 8–10 %, density value of 2500 kg/m³, and specific heat capacity value of 900 J/kgK. The temperature distribution results of the natural state model show the fluid flow path in the Ulumbu geothermal system. The Ulumbu field geothermal system belongs to the natural two-phase system with an average temperature above 225 °C.

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