A natural state model and resource assessment of Ulumbu Geothermal field

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Abstract. Ulumbu Geothermal Field is located in Manggarai District, Flores Island, Indonesia. Downhole measurement results indicate that this field has a vapor-dominated reservoir overlying liquid-dominated reservoir with temperatures of 230-240°C. Based on the previous study it is the most promising prospect on the island of Flores with 100 MWe possible reserve. The objectives of this study are to discuss a natural state model of Ulumbu geothermal field and to assess its potential resource. The natural state model has been successfully constructed by using geological, geophysical, geochemical, and wells data from several published literature. The model can be categorized as valid since the model temperature, mass flow, and heat flow agree with the observation data. Although there might be still room for further improvements. Based on the parameters obtained from the reservoir characterization, the potential resource of the field was successfully calculated by using heat stored method with Monte Carlo probabilistic simulation. The resource calculation result indicates the field has a good capability of supporting current installed capacity with a high level of confidence.

1. Introduction

Ulumbu Geothermal Field (Figure 1) lies in Manggarai district, 13 km from the nearby city, Ruteng, East Nusa Tenggara, Indonesia. Based on the previous study, it is the most promising prospect on the island of Flores with 100 MWh discharges from this field [3]. Further study by [1] and [8] indicated a possible reserve of 100 MWe and a potential recoverable reserve of about 150 MWe respectively. Based on downhole measurement results, the geothermal system of this field is vapor-dominated at the upper part and liquid-dominated at the lower part with temperature approximately 230-240°C [5][2]. This field is a part of a government program called Flores Geothermal Island whose purpose is mainly to raise the use of geothermal energy both as a direct and indirect utilization in the island.

In [4], the preliminary studies in the period of 1969 to 1980’s were carried out by Volcanological Survey of Indonesia, PERTAMINA, and PLN. Moreover, in the period of 1980’s to 1992, the feasibility study was done by KRTA Limited. In 1994-1996, the exploration and production drilling studies were held by PT PLN. Three wells were drilled in the area namely ULB-01, ULB-02, and ULB-03. This field has been producing a total capacity of 10 MW and has been supported only by ULB-02 [5].
Figure 1. Location of Ulumbu Geothermal Field (Google Maps, 2018).

Given that this field has a considerable number of data, the natural state modeling and the resource assessment can be carried out. However, the model was only constructed based on a few number of data as limited availability of the published data. The resource assessment calculation used heat stored method with some parameters obtained from the natural state model. The heat stored method was combined with Monte Carlo simulation as the simulation takes into account the uncertainties of the parameters in resource calculation.

The result is 103 MWe showing this field has a good capability of supporting current installed capacity with a high level of confidence. All in all, the natural state model and the resource assessment of Ulumbu Geothermal Field have been done successfully.

2. Conceptual Model Review

2.1. Geosciences

Geoscience studies have to take into account in building natural state model. Following paragraphs describe the geology, geochemistry, and geophysics studies based on several published papers.

Flores Island is situated on the inner of two concentric ridges which form a part of an active subduction system that extends for about 2,000 km east from Java Island [7]. North west oriented faults are prominent in the island, they are associated with an east west trending fold axis which is consistent with subduction along an east west axis [4].

The following geological reviews are based on [7]. The rocks in this area consist of two ages, quaternary and tertiary rock. The tertiary volcanic rocks comprising mainly lavas, breccias, tuff, and calcareous sediments act as the basement, meanwhile, the quaternary rocks spread to an elevation of approximately 1,600 masl. Those two units of rock were penetrated by the deepest and vertical well ULB-01, i.e., volcanic rock unit to a depth of 815 m which divided further into two sub-units and a bioclastic limestone and volcaniclastic rock unit from 815 m to 1,887 m. The upper sub-unit of volcanic rock has thickness of approximately 665 m and composed of volcanic breccia with thin intercalations of andesite lava and tuffs. The lower sub-unit of volcanic rock has thickness of approximately 150 m with thinner intercalations. The lowest unit, the bioclastic limestone and volcanioclastic sediments unit is approximately 1,072 m thick and consists of particularly bioclastic limestone with intercalations of volcanic sandstone, siltstone, basaltic lavas, and tuff.

Surface manifestations in Ulumbu geothermal field mainly comprise of hot spring, fumarole, and rock alteration. The majority of the thermal features are located within the crater on the western and southwestern of Poco Leok complex with the total area of approximately 28 km² [3]. Those
manifestations are largely found at the inner rim structure and in the vicinity of NW-SE faults showing those faults are probably acting as the main conduit controlling geothermal activity in this field.

Based on [6] there are three groups of hot springs. Near boiling point hot springs are located in the river of Waikokor Valley while the hot springs and warm springs are located 1.5 km east and 5 km west of Ulumbu respectively.

The following geochemistry explanations are based on [4]. Fumarole gases which mainly contain CO₂ and H₂S have a concentration of 2-3% weight with a CO₂/H₂S ratio of 20 to 30. There was no evidence proved the presence of magmatic volcanic type gases such as SO₂ or HCl from the discharged steam. Geothermometry of the fumarole gases at Wai Kokor indicates that the fluid is derived from a deep fluid source with temperature probably greater than 250°C and possibly as high as 300°C. However, the exact location of the source is not clear whether it is below the fumaroles or at some distance horizontally around them. The water chemistry suggests that the warm springs in the west are further from the source than those at Kokor or Lungar and together with the steam and gas results, suggest that the major upflow zone is beneath Kokor or towards Lungar. That fact might also indicate that the main outflow zone is located west of Ulumbu geothermal field.

The soundings resistivity study indicates that low resistivity layer sandwiched between an upper shallow layer and higher resistivity basement [4] while the MT study which is distributed from Ulumbu to Mucu area, inside the Pocoleok Caldera, shows the presence of low resistivity zones with rocks composed of lava and pyroclastic alteration material. The clay alteration shows smectite, pyrophyllite, alunite, kaolinite, and illite, which are part of clay cap having thickness from 500 to 700 m [5]. It is also stated that the low resistivity zone has an area of approximately 50 km² and is deeper east of Ulumbu [4]. The boundary is clearly defined to the north and the west, but it is opened to the south and east. The higher resistivity values of 10-50 ohm-m exist at the deeper section, such high resistivity indicates the presence of reservoir layer having thickness of 800 m to more than 1,500 m [5].

2.2. Wells Data
Three drilled wells namely ULB-01, ULB-02, and ULB-03 were drilled at the same wellpad, 100 m south of fumaroles. ULB-01 well has a total depth of 1,887 mTVD while the other wells have a total depth of 878.6 mMD and 951 mMD for ULB-02 and ULB-03 respectively. ULB-02 well is the only active production wells supporting all 10 MWe installed capacity.

From the discharge test on [2], the temperature measurement for all wells indicates nearly the same results, meanwhile, the pressure profiles show the liquid zone beneath the steam column. The lower section of the three wells is probably a liquid-dominated reservoir as the evidence show there are downflows within the liquid column and also there is liquid discharged from ULB-01.

Figure 2 depicted the shut-in temperature profiles for all wells. The ULB-01 temperature profile is a result of 30 days of heating, the maximum temperature of 237°C presents at an elevation of 490 mbsl. There is also temperature inversion occurs at depth of 695 m where the temperatures decrease from 230°C to 206°C [7], it is probably due to the presence of cold inflow from major permeability zone at this depth [6]. The temperature inversion at ULB-01 indicates this well is not located above the upflow zone of the geothermal system, the upflow is presumably located upslope from the existing well [2].

The ULB-02 temperature profile is a result of 11 days of heating [3]. At depth of 700 m, the temperature reversal also occurs, the temperature changes from 239°C to 225°C and it is associated with total lost of circulation at this zone [7]. The ULB-03 temperature profile is a result of the longest shut-in period compared to other wells, it had been closed for about 7 months [3], but did not show any clear indication whether or not there was a convective regime in the borehole.
2.3. Conceptual Model
Conceptual models are a descriptive and qualitative model which provides a whole description of the structure and nature of the system in question. The models were constructed from integrated geological, geochemical, geophysical, and wells data. Figure 3 shows the conceptual model of the field by using slice plan NE-SW. It depicts the components of a geothermal system such as heat source, reservoir, cap rock, recharge, and discharge area. Isotemperatures profile and steam cap zone are also shown.

3. Natural State Model

3.1. Model Description
The model in this study has a total area of 10x10 km² with a vertical extent of approximately 4.4 km. The model was rotated clockwise to accommodate predominant structure and flow direction. The vertical extent of the model was discreted into 16 layers with several layers at the above part to follow the real topographical condition. Rectangular grid approximation is used and the overall number of the grid blocks are 16,384. The grid block sizes vary depending on the geological condition, smaller grid blocks are used at the center area, where the reservoir and the wells are situated, to adequately mimic the geological condition. Figure 4 depicts the gridding area of the model.

The rock properties such as specific heat, wet heat conductivity, rock density, and porosity were kept constant as at the initial condition since only the permeability is considered to be the most significant parameter in natural state modeling. The permeability values were continuously adjusted until the pressure as well as the temperature distribution of the model correspond to the observation data. The final permeability values were obtained from dozens of trial and error attempts. Table 1 shows the final permeability values of each rock type while Figure 5 depicts the final rock properties distribution.
The following initial and boundary condition were defined to simulate the reservoir system. Hydrostatic pressure and normal temperature gradient for both temperature and pressure were used at the initial condition. The top boundary was set to be at an atmospheric condition of 25°C and 1 bar with huge volume factor to let the parameters remain in the initial condition. The side boundary is assumed to be no flow boundary and its materials are treated to be impermeable. The bottom boundaries are heat source and impermeable rocks. The heat source is presented using several blocks having constant temperature and pressure of 306°C and 157 bara. The heat source location was initially based on conceptual data, but it needed to be adjusted to achieve the best model output which corresponds to the actual data.

To simulate the rain infiltration, the surface injection was added based on annual rainfall data of Flores Island of 2,500 mm/year with assumed infiltration rate of 10%. The recharge rates of each grid block size are different for one to another. It is assumed that the injected water has a temperature of 25°C and enthalpy of 104.8 kJ/kg.
Table 1. Permeability values for each rock type.

| Material | \( k_{xy} \) (mD) | \( k_z \) (mD) | Color |
|----------|------------------|----------------|-------|
| ATM      | 0.4              | 0.2            |       |
| GW       | 0.1              | 0.1            |       |
| CAPR     | 0.05             | 0.05           |       |
| FAULT    | 100              | 50             |       |
| RES1     | 150              | 75             |       |
| RES2     | 20               | 10             |       |
| RES3     | 75               | 75             |       |
| ROCK1    | 0.01             | 0.01           |       |
| ROCK2    | 0.001            | 0.001          |       |
| ROCK3    | 0.1              | 0.05           |       |
| ROCK4    | 0.1              | 0.1            |       |
| ROCK5    | 0.0035           | 0.0035         |       |
| ROCK6    | 0.006            | 0.006          |       |
| HS       | 100              | 100            |       |

3.2. Modeling Result

Several parameters need to be validated using observation data in order to reach the natural state condition. All in all, the model successfully reflects the real condition.

The model was run until steady state condition with the simulation time was greater than the geological time. Model heat distribution and mass flow are depicted in Figure 6. The figure shows the good agreement between the model and the real condition 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 which correspond to those of conceptual model. The upflow zone located between Poco Leok and Poco Rii depression while the outflow zone towards west. The recharge area was also successfully modeled as indicated by the fluid flow direction from the west and east towards the reservoir area.

Figure 6. Model temperature distribution and mass flow profile.
Furthermore, Figure 6 also indicates a good correspondence between model heat flow with the conceptual model as indicated by the temperature distribution pattern. Moreover, the heat flow was also validated by using well temperature and fluid condition in the reservoir. Well data were obtained from shut-in temperature of ULB-01, ULB-02, and ULB-03. Figure 7-9 show the comparison between model temperature and observation temperature of those wells. Those figures indicate the well temperature obtained from the model are well-matched with the actual data, although there is still room for further improvements.

![Figure 7. ULB-01 well temperature matching.](image)

![Figure 8. ULB-02 well temperature matching.](image)

![Figure 9. ULB-03 well temperature matching.](image)

The fluid condition of reservoir is evaluated by analyzing the presence of vapor-dominated zone overlying liquid-dominated reservoir in the model, it was successfully presented as shown by Figure 10.
4. Resource Assessment

Because there are vapor dominated and liquid dominated zone in the reservoir, the resource calculation would be divided into two sections.

4.1. Reservoir Characterization

Before conducting the resource assessment calculation, the parameters needed are acquired from the reservoir characterization. The reservoir area was obtained from the delineation of high temperature reservoir defined by Hochstein of 225°C. Figure 11 indicates the reservoir area at a representative elevation. The reservoir area is approximately 22 km². The reservoir thicknesses are based on temperature profile of the deepest well, ULB-01, and the natural state model. The vapor and liquid dominated zone have a thickness of about 600-800 m each.

Rock porosity and density are obtained from common rock properties. The porosity values are in range of 7% while the rock density values are 2400-2650 kg/m³. The rock heat conductivity values of 950-1000 J/kg·°C are based on [9] for volcanic and sedimentary rocks at 230-240°C.
The initial water saturation for the vapor dominated zone is 0.3-0.35 based on the natural state model, while for the liquid dominated zone it is 0.65-0.7. The final water saturation for the vapor dominated zone is 0 because the superheated condition is assumed at the end of the project life. The values of 0.3-0.5 are assumed at liquid dominated zone at the final condition.

The initial reservoir temperature is obtained from well temperature. The initial temperature of the vapor dominated and liquid dominated zone are 239°C and 230°C respectively. The abandonment reservoir temperature is 180°C based on National Standard of Indonesia for high temperature geothermal system.

The recovery factor is obtained by correlation proposed by Muffler [10]. The recovery factor is 2.5 times the porosity value. The recovery factor is about 17.5%. The conversion efficiency was selected using [11], the value is a function of reservoir temperature. It is obtained that for the reservoir temperature of 230-236°C, the thermal conversion efficiency values are in range 10.9-11.4%. The project lifetime is assumed to be 30 years.

4.2. Resource Estimation
To assess the power generation ability of Ulumbu Geothermal Field the heat stored method with probabilistic approach (Monte Carlo simulation) was conducted. This simulation was run by using 60,000 random numbers.

Parameter values used in the calculation were acquired from the previous section. The Monte Carlo simulation was conducted two times to differentiate the vapor and liquid dominated zone calculation.

The total of both calculations resulted a value of 103 MWe for the possible reserve. The result is close to possible reserve estimation calculated by [1] of 100 MWe. It also indicates a high confidence level of Ulumbu Geothermal Field in generating the current capacity of 10 MWe. It even shows a good possibility of Ulumbu Geothermal Field to be developed to a greater capacity in the future.

On the other hand, the result does not correspond to the calculation by [8] of 150 MWe. It is hard to trace the cause because the method and the parameters used in that calculation are not known.

5. Conclusion
The natural state of Ulumbu geothermal field was successfully developed as indicated by well-matched profiles between the model and the actual condition.

The possible reserve of 103 MWe from the heat stored calculation indicates a high level of confidence of Ulumbu Geothermal Field to host the current installed capacity of 10 MWe. It even shows a good indication of Ulumbu Geothermal Field to be developed further beyond the current production capacity. The result also agrees with the reference, although there is still room for further discussion if more published data were available.

References
[1] Ditjen EBTKE 2017 Buku Potensi Panas Bumi Indonesia Jilid 2 Kementrian ESDM Indonesia.
[2] Grant M A Hole H and Melaku M 1997 Efficient Well Testing at Ulumbu Field, Flores, Indonesia Proc. Stanford Geothermal Workshop Stanford California.
[3] Kasbani Browne P R L Johnstone R D Kahsai K Utami P and Wangge A 1997 Subsurface Hydrothermal Alteration in The Ulumbu Geothermal Field, Flores, Indonesia Proc. Stanford Geothermal Workshop Stanford California.
[4] Mahon T Modjo S and Radja V T 1992 The Result of Joint Scientific Study of The Flores Ulumbu Geothermal Area Geothermal Resource Council Transaction 16.
[5] Nasution A Yunis Y and Afif M 2016 The Ulumbu Geothermal Development West Flores Eastern Indonesia The 11th Asian Geothermal Symposium Chiangmai Thailand.
[6] Sulasdi D 1996 Exploration of Ulumbu Geothermal Field, Flores-East Nusa Tenggara Indonesia Proc. 21st Workshop on Geothermal Reservoir Engineering Stanford University Stanford California.
[7] Utami P Browne P R L 1996 Petrology of Cores and Cutting Samples from ULB-01 and ULB-
02, Ulumbu Geothermal Field Flores, Indonesia Proc. Indonesia Petroleum Association.

[8] WJEC 2008 Pre-Feasibility Study for Geothermal Power Development Projects in Scattered Islands of East Indonesia Study Report.

[9] Schon J H 2011 Physical Properties of Rocks A Workbook Handbook of Petroleum Exploration and Production Elsevier Netherlands 8 337-361

[10] Muffler L P J and Cataldi R 1978 Methods for Regional Assessment of Geothermal Resources Geothermics 7 53-89

[11] Nathensson M 1975 Physical Factors Determining The Fraction of Stored Heat Recoverable from Hydrothermal Convection Systems and Conduction Dominated Areas USGS Menlo Park CA Unites States, open file report 75-525, 51 pp