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Probabilistic approach of resource assessment in Kerinci geothermal field using numerical simulation coupling with monte carlo simulation

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Abstract. The Kerinci geothermal field is one phase liquid reservoir system in the Kerinci District, western part of Jambi Province. In this field, there are geothermal prospects that identified by the heat source up flow inside a National Park area. Kerinci field was planned to develop 1×55 MWe by Pertamina Geothermal Energy. To define reservoir characterization, the numerical simulation of Kerinci field is developed by using TOUGH2 software with information from conceptual model. The pressure and temperature profile well data of KRC-B1 are validated with simulation data to reach natural state condition. The result of the validation is suitable matching. Based on natural state simulation, the resource assessment of Kerinci geothermal field is estimated by using Monte Carlo simulation with the result P10-P50-P90 are 49.4 MW, 64.3 MW and 82.4 MW respectively. This paper is the first study of resource assessment that has been estimated successfully in Kerinci Geothermal Field using numerical simulation coupling with Monte Carlo simulation.

Keywords: Kerinci, numerical simulation, resource assessment, monte carlo

1. Introduction

Kerinci geothermal field is located in the Kerinci district, western part of Jambi province (5 km to the NE of Sungai Penuhtown) and approximately 525 km from Jambi capital city. This field has been developing by PGE since 2008 due to the energy shortage and to meet power demands that increase 9-10% per year in South Sumatra. Jambi province needs 275 MW of electrical power in the next five years, almost double increase from the current peak load of 150 MW. The electricity power in Kerinci area generated by the old diesel fuel engine, black out almost every night and no industrial growth, so that the local government support PT. PGE to explore the geothermal resources of Kerinci (Silitonga, 2015). Figure 1 presents the location of the Kerinci Geothermal Field.
2. Objectives
The objectives of this study are following:
1. To develop numerical model of Kerinci Geothermal Field which achieved natural state condition by using TOUGH2 software.
2. To validate pressure and temperature profile of the model and measured data from KRC B-1 wells
3. To characterize reservoir that including area, thickness, pressure, temperature, and permeability distribution.
4. To determine geothermal energy reserve of numerical model of Kerinci Geothermal Field by heat stored method with deterministic and probabilistic approach.

3. Conceptual Model
Conceptual model is the key to create numerical modelling. It is generated based on geological, geophysical, geochemistry and well survey data. The conceptual model of Kerinci geothermal field contain heat source location beneath M. Kunyit, iso temperature distribution, recharge location, distribution of surface manifestation, and well location (figure 2). The heat tends flowing to the NE. Permeable zone is about lower than 700 m. The conceptual model is used for numerical model as main based.
4. Methodology
In development of numerical model of natural state, there are several steps that must be undertaken. These steps are designed based on conceptual model to change parameters in TOUGH2 software and presented by flow chart at figure 3.

The first step is to create computer model based on conceptual model. The next step, input data including material properties and boundary condition. Then, Run the model and result of numerical model will be calibrated. If the calibration is reached, natural state model is obtained. But if not, back to input data to change the material until natural state.

From the natural state model, the author characterize the reservoir to obtain parameters value as data input for resource estimation. The resource estimations are used heat stored as a deterministic approach and heat stored with Monte Carlo simulation as probabilistic approach.

5. Numerical Model

5.1. Grid Model
The model of grid is developed in three dimensional. The model is aligned at 50°NE with a covering total area of 4.75 km × 3.5 km or equal to 16.25 km². Elevation of this model is started from 1410 masl to -2000 masl or total thickness is 3410 m. The model consists of 7820 (23 × 17 × 20) blocks. The grid blocks is present detail in table 1.

The numerical model used EOS1 (water, water with tracer) type and used single porosity system to simplify the model. The 3D numerical model is presented in figure 4.

The model of grid system is used to follow parameter approaching. The main reservoir used smallest size and the boundary condition used biggest grid block size. The parameters that used through the model are heterogeneity approaching.

This numerical model is used to simulate reservoir performance by properties input including rock and fluid. The best model is obtained by good match pressure and temperature profile of simulation and measured well data. In Kerinci Field, there is one exploration well (KRC-B1) that has pressure and temperature profile data to be matched with simulation data.

5.2. Material Properties
Materials are used to define the permeability and other properties in an analysis. After the model of grid was built, this numerical model creates materials to approach the simulation with actual condition with rock properties based on conceptual model. Materials can be assigned by layer, by region, or to individual block.
Figure 3. Flow chart of numerical model of natural state.
Table 1. Grid block system

| Direction (x,y,z) | Grid blocks | Grid block size (m) |
|------------------|-------------|--------------------|
| x                | 1           | 250                |
| x                | 1           | 225                |
| x                | 19          | 200                |
| x                | 1           | 225                |
| x                | 1           | 250                |
| y                | 1           | 250                |
| y                | 15          | 200                |
| y                | 1           | 250                |
| z                | 1           | 10                 |
| z                | 4           | 150                |
| z                | 8           | 100                |
| z                | 4           | 200                |
| z                | 3           | 400                |

The properties that must be inputted are specific heat, wet heat conductivity, rock density, porosity, permeability (x, y, z direction). The main parameter in material properties to develop numerical model of natural state is permeability structure.

Figure 4. The 3D Numerical Model of Kerinci Field

5.3. Boundary and Initial Condition

5.3.1. Initial Condition

Initial condition are used to define the initial state of each block of numerical model. In the condition, it is depend of EOS and phase type. In this numerical model is used EOS1 and single-phase based on actual
condition. The next step, define initial pressure and temperature condition in all grid blocks. The pressure and temperature is stated by equation with depending some variables. The equation is presented by equation (1) and (2). The equation (1) and (2) is used by gradient of well data to approach in numerical model. The equation of gradient pressure:

\[ P = 1.14 \times 10^7 - 8000z \]  
(1)

And the equation of gradient temperature:

\[ T = 81.4 - 0.04z \]  
(2)

Where : \( P \) is pressure (Pascal), \( T \) is temperature (°C) and \( z \) is depth (m).

5.3.2. Top Boundary
Top of numerical model of natural state is located at the water table and there is atmospheric condition assumed by pressure at 1 bar \( (1.01 \times 10^5 \text{ Pa}) \) and temperature at 25°C. In this boundary, the materials used big volume factor, a multiplier on the volume that used to obtain the final volume. It means, the value of pressure and temperature in this materials along simulation tends to be constant from initial condition. In below of atmosphere layer is groundwater layer that used another big volume factor. But the volume factor is smaller than atmosphere volume factor to make simulation process to be continuously convergent.

5.3.3. Side Boundary
This numerical model is assumed all side of boundaries in closed condition (no mass and heat flow). This boundary is used low permeability \( (10^{-18} \text{ m}^2 \text{ or } 0.001 \text{ mD}) \) and big volume factor \( (10^{20}) \).

5.3.4. Bottom Boundary
Bottom boundary was set heat sources and basement rock materials. Heat sources material was set by pressure and temperature based on JICA report (1989). From JICA (1989), temperature heat sources is around 300 – 320°C. The pressure and temperature of heat source is greater than surrounding materials and the value pressure at 252 bar and temperature at 300°C tend to be constant.

**Table 2. Layer Properties for the initial numerical model.**

| Layer          | Top, Bottom (masl) | Layer          | Top, Bottom (masl) |
|----------------|--------------------|----------------|--------------------|
| Atmosphere     | 1410, 1200         | Reservoir6     | 300, 200           |
| Ground water   | 1400, 1250         | Reservoir7     | 200, 100           |
| Cap Rock1      | 1250, 1100         | Reservoir8     | 100, 0             |
| Cap Rock2      | 1100, 950          | Reservoir9     | 0, -200            |
| Cap Rock3      | 950, 800           | Reservoir10    | -200, -400         |
| Reservoir1     | 800, 700           | Reservoir11    | -400, -600         |
| Reservoir2     | 700, 600           | Reservoir12    | -600, -800         |
| Reservoir3     | 600, 500           | Basement Rock1 | -800, -1200        |
| Reservoir4     | 500, 400           | Basement Rock2 | -1200, -1600       |
| Reservoir5     | 400, 300           | Basement Rock3 | -1600, -2000       |
Table 3. Layer Properties for the initial numerical model.

| Material          | Color | Permeability-$x$ (mD) | Permeability-$y$ (mD) | Permeability-$z$ (mD) | Porosity |
|-------------------|-------|-----------------------|-----------------------|-----------------------|----------|
| Atmosphere        |       | $1.0 \times 10^9$     | $1.0 \times 10^9$     | $1.0 \times 10^9$     | 0.99     |
| Ground Water      |       | 0.025                 | 0.025                 | 0.025                 | 0.07     |
| Cap Rock          |       | 0.05                  | 0.05                  | 0.05                  | 0.05     |
| Reservoir 1       |       | 10                    | 10                    | 20                    | 0.1      |
| Reservoir 2       |       | 10                    | 10                    | 10                    | 0.1      |
| Basement Rock     |       | 8                     | 8                     | 4                     | 0.1      |
| Side Boundary     |       | 0.001                 | 0.001                 | 0.001                 | 0.05     |
| Heat Source       |       | 10                    | 10                    | 10                    | 0.1      |

6. Natural State

6.1. Numerical Model Calibration

The main purpose in this numerical model is to achieve the natural state. So that, this paper in model calibration is focusing to match the natural state. This natural state has been described completely in previous paper at IIGCE event 2016 (Iki, 2016). There are two general steps to achieve natural state model, those are first estimates of model parameters from the conceptual model and calibration of the permeability structure by natural state modelling. In the first estimates, next step the numerical model is ran by TOUGH2 software. The first important in running of simulation is ensuring the numerical model to achieve steady state condition in the end of simulation running. It means, the value of DT (solution time increment) is increasing to converge.

After steady state condition in simulation result, compared with actual pressure and temperature profile. If the result of matching between simulation data and actual data is not good, the parameters in TOUGH2 were adjusted in and iterative process.

The following are several ways to adjust this numerical model in calibration of natural state:
1. The pressure and temperature of heat sources are adjusted.
2. The size grid blocks of heat sources
3. Permeability structure in $x$, $y$, $z$ direction is adjusted in accordance of layer location.
4. Construction of suitable material in each layer based on conceptual model.
5. The amount of materials are made in accordance based on conceptual model
6. The amount of layers in the reservoir

After the result of pressure and temperature profile are good fit, the next step to ensure direction of fluid and heat transfer movement is right. The model must be adjusted recharge location that affect direction of fluid movement. In caprock and boundary zone, there are no fluid movement although opposite direction because the zones are impermeable rock. In direction of heat transfer, the movement will pass through permeable zone by convection but heat transfer will pass by conduction through impermeable zone.

6.2. Comparison of Pressure and Temperature Profiles

Kerinci geothermal field has three exploration wells but two of them are slim hole well. To compare pressure and temperature profiles between simulation and actual data, the author used KRC-B1 well for calibration process because available actual data considering. The result in comparison of pressure and temperature numerical model Kerinci geothermal field from KRC-B1 well is presented in previous paper respectively.

Based on figure 5, the result of pressure profile between actual data and simulation data is very good matching. In this figure, there is one simulation data in -500 m elevation but there is no actual data. It means
that the simulation data is drilling well to -500 m. The gradient pressure in KRC-B1 well is about 0.08 bar/meter. But this numerical model need more well data to validate gradient temperature each location. If gradient pressure in two or more wells data tends to be similar, it means numerical model has one heat source and interconnected. But for this case, the author assumes that Kerinci geothermal field has one heat source only.

In figure 6, the result of temperature profile between actual data and model data is suitable matching. But there are a little bit different in temperature reservoir. In the reservoir elevation, the temperature actual tends to constant (209 - 211°C) but in the temperature model is varying (207 - 217°C). It is caused probably the materials of this numerical model is less of many kinds in construction. But the more well data are used, the better numerical model is validated. The bellow, comparison of conceptual model and natural state result are shown in figure 7. Size of numerical model area is shown in E’ to E vertical line.

6.3. Heat and Fluid Flow
Heat and fluid flow is one of calibration processes in the numerical model. Based on conceptual model, there are two recharges location in Kerinci geothermal field. Those recharges is located in southwest and northeast. It will affects direction of heat and fluid flow. In result of numerical model of Kerinci geothermal field, heat from heat sources flows to upward through permeable zone. But heat flow was halted in impermeable zone including side boundary and caprock. At near both materials, the heat flow is reversed flowing to bottom and establish a circle. In another point, heat tends to move from heat sources location towards the east. It is caused of permeable zone in that area. In reservoir zone, the heat transfer was occurred by convection. But in caprock and side boundary, heat transfer was occurred by conduction.

The result of fluid flow in numerical model of Kerinci geothermal field, the path flow is similar with the heat flow. Basically, the fluid flow will be followed by heat flow, it is called convection. Heat is still flowing in impermeable zone by conduction but fluid could not flow in impermeable zone. As a result, there are other fluid from recharge that cause fluid flow downward.

In numerical model is a little different about topography with conceptual model. The fact of surface in Kerinci field is not flat, mainly in the top of Kunity Mountain. Assumption in top elevation of numerical model is flat at highest elevation of well (1410 masl). The purpose of the assumption is simplification to construct the numerical model and the top of numerical model is used to accommodate wells. One of types of top boundary conditions is used along a boundary about fixed value of temperature (Franco, 2013).
Before the boundary condition is defined, first the definition of geological element or topography (Franco, 2013). The consequently, fluid will flow from top of Kunyit Mountain to underneath and the pressure in around the top of mountain will be higher than surrounding.

From conceptual model of Kerinci geothermal field, it was existed Duabelas fault. But in the numerical model is not exist because the author assumed that the fault area is neglected because it is very small and the material is homogeneity with reservoir material. In fact in fault area, the permeability is higher than surrounding.
6.4. Permeability Distribution
Permeability structure is most influence in the numerical model. It will affect heat and fluid flow, pressure distribution and temperature distribution. In numerical model of Kerinci geothermal field, permeability is important parameter to achieve natural state. This numerical model needs heterogeneity in \( x, y, z \)-direction permeability. It is caused temperature profile in Kerinci geothermal field is not symmetry as well as also heat and fluid flow.

The reservoir permeability is the main permeability in numerical model of Kerinci geothermal field. The result of this numerical model, highest permeability value reservoir is in Reservoir-1 material. The value of \( x, y \)-direction is a half of value of \( z \)-direction in reservoir-1 material. In Reservoir-2, the value of \( x, y, z \) direction is the same. In basement rock permeability is lower than Reservoir-2. The value of permeability \( x, y \)-direction in basement rock is lower than \( z \)-direction. It is caused there are big effect of gravity in bottom of reservoir. So that the value of \( z \)-direction permeability in basement rock is small.

![Figure 8. Permeability distributions at 50 masl (reservoir-1 and side boundary)](image)

6.5. Reservoir Characterization
Based on result of numerical modelling of natural state, the model could determine reservoir characterization. The area reservoir in this model covered about proven and probable area. The proven area is bounded by three exploration wells. The proven area is covered about 5.5 km\(^2\). Probable area is bounded by surface manifestation and the area is covered about 8.5 km\(^2\). Reservoir has thickness about 1500 m. Permeability range in the reservoir is varying between \(5 \times 10^{-15} \text{ m}^2\) (5 md) and \(1 \times 10^{-14} \text{ m}^2\) (10 md).

This model has single phase liquid, so that the system reservoir in the Kerinci geothermal field is one phase liquid reservoir where temperature reservoir is lower than the saturation temperature, presented in figure 11.
Figure 9. Permeability distributions at -50 masl (reservoir-2 and side boundary).

Figure 10. Permeability distributions at -875 masl (reservoir-2 and side boundary).
One phase liquid could be shown with saturation from result of numerical model. It is clearly that the gas saturation of natural state Kerinci is 0. The following is saturation gas in result of numerical model in figure 12.
6.6. Resource Estimations

The estimation of resource in Kerinci geothermal field used heat stored principal. There are two methods including deterministic and probabilistic approach. Deterministic approach used volumetric method and probabilistic approach used Monte Carlo simulation.

The volumetric method needs some parameters including area, depth, porosity, rock density, heat rock capacity, initial and final water saturation, initial and final temperature, recovery factor, conversion factor, and project time. The parameters is obtained from conceptual model, reservoir characterization, general assumptions. The result of resource by volumetric method is 57 MWe. The detail of result is presented in figure 13. From the result of volumetric method as deterministic approach, the author could analyze the sensitivity of parameters. The most influencing parameters are area and recovery factor.

Monte Carlo simulation is calculation of iterations from probabilistic model that simulate properties physic in distribution value for estimating geothermal resource by heat stored principal. In this simulation, the author estimate minimal, maximal, and mostly value in each parameter of geothermal resource.

The proven area in Kerinci geothermal field was bounded by three exploration wells. It means the area has proven in geothermal resource by drilling well. So that, the proven area is obtained. The probable area is obtained from reservoir characterization based on surface manifestation distribution.

The thickness of reservoir is obtained from high temperature profile. From high temperature profile, the thickness is from 500 masl down to -500 masl. But the thickness is added by reservoir-2 material based on temperature distribution in result of numerical model. The thickness of the reservoir is approximately about 1500 m. Rock porosity is obtained from relation of rock type and porosity value (B. Layman and Soemarinda, 2003). The rock porosity is obtained about 0.15. Recovery factor is obtained from correlation between recovery factor and porosity (After Muller, 1978), the value is about 0.375. Conversion factor is obtained from correlation between conversion factor and reservoir temperature (Nathenson, 1975 and Bodvarson, 1974), the value is about 10%. The project time of Kerinci geothermal field is assumed about 30 years.

In this Monte Carlo simulation, the numerical model of Kerinci geothermal field was resulted the value geothermal resource by the type of degree confidence rank (P10, P50, and P90). The highest degree confidence respectively from P10, P50, and P90. Input parameters value for Monte Carlo simulation is shown in figure 18.

The result of Monte Carlo simulation, the value of Kerinci geothermal P10 is 49.4 MWe, P50 is 64.3 MWe, and P90 is 82.4 MWe, presented also in figure 14. Based on Monte Carlo simulation calculation, the geothermal potential of kerinci geothermal field is lower than 55 MWe for highest degree confidence.

![Sensitivity Analysis](image)

**Figure 13.** Resource calculation results based on deterministic heat stored method with sensitivity analysis
Figure 14. Resource calculation results based on Monte Carlo simulation.

7. Conclusion
From this numerical modelling the following conclusions can be summarized:
1. The first numerical model of natural state of Kerinci geothermal field has been successfully developed.
2. Pressure and temperature profile between model data and KRC-B1 well data is very good matching.
3. From reservoir characterization is obtained proven and probable area, thickness reservoir, reservoir permeability range, temperature reservoir and system reservoir fluid.
4. This numerical model of natural state Kerinci geothermal field could generate electrical around 57 MW with heat stored method as deterministic approach. But the probabilistic method using heat stored with Monte Carlo simulation for P10-P50-P90 are 49.4 MW, 64.3 MW and 82.4 MW respectively.

8. Recommendation
1. To ensure geothermal potential, this numerical model should be more validated of using other well data.
2. This numerical model should be improved by validating with existence of fault in around of reservoir.
3. This numerical model should be considered about topography and surface manifestation distribution.
4. This numerical model should be applied by using experimental design to generate probabilistic resource assessments result.
5. For further study, this numerical model could be forecasted in the future scenario.

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