Updating the Conceptual Model of Cisolok-Cisukarame Geothermal field, West Java, Indonesia

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Abstract. The cisolok-cisukarame geothermal field is a liquid dominated geothermal system situated in Sukabumi District, West Java, Indonesia. Geothermometry survey shows that Cisolok-Cisukarame has temperature approximately 185-212°C in the reservoir. The temperature of the reservoir shows that this is a medium enthalpy geothermal system. The thermal manifestation distributed around the Cisolok-Cisukarame area when the Cisukarame indicated as the upflow zone and Cisolok as the outflow zone. It is located at the eroded volcanic area with cooling pluton acting as the heat source of the system. Based on EBTKE, Cisolok-Cisukarame geothermal field has 45 MWe possible reserve. NE-SW and N-S faults are acting as the main conduit of the geothermal system. The primary purpose of this study is to build a computer model describing the natural state condition based on the geological, geochemical, geophysical, and well temperature data from several published literature. The model was validated by using mass-heat flow profile obtained from the observation data to achieve the best representation of the actual condition. The condition was achieved by modifying the permeability structures and productivity index. This model is the first natural state model of Cisolok-Cisukarame geothermal field. The natural state model then is used to build an updating conceptual model of Cisolok-Cisukarame by using data from a result of numerical modeling. Based on the parameters obtained from the numerical modeling, a new model of Cisolok-Cisukarame geothermal field is successfully representing the heat and mass flow within the system.

1. Introduction
The cisolok-cisukarame geothermal field is located in Sukabumi District, West Java, Indonesia, it is approximately 150 km from Jakarta as shown in Figure 1. The total geothermal working area of this field is about 15.580 Ha. The temperature of the reservoir is approximately 185-212°C. Based on the temperature of the reservoir, the geothermal system of this area can be categorized as a medium enthalpy geothermal system [1]. This field has a possible reserve of about 45 MWe [2].

This field exploration activity has begun since 1970 by PT. Pertamina. Several surveys had been conducted, such as detailed geology, detailed geochemistry, and geophysics including DC resistivity, SP, MT, gravity. The first well being drilled was CSL-01 with 1477 m depth. There have been several additional wells drilled in the area, but CSL-01 data is the only available published data.
This Cisolok-Cisukaram is owned by PT. Jabar Rekind Geothermal. The current status of this field is still in the exploration phase. In the future, this field is plan to have 45 MWe installed capacity, supplied from the first unit, in 2025 [2]. The plan in 2025 is an optimistic target when the data of this field are limited. The limited data cause high uncertainty and inaccurate interpretation, mainly when the conceptual model has not represented the actual heat and mass flow within the Cisolok-Cisukaram geothermal system.

The natural state study can be carried out with sufficient accuracy because the field has a considerable number of accurate data. The model can be used to understand the mass-heat flow profile of the reservoir at its initial condition as well as to understand the behavior of the unexplored area of the reservoir. This model can be used to build an updated conceptual model of this geothermal system to describe the heat and mass flow within the system. Some updated conceptual models of geothermal fields were successfully built using numerical simulation results. The previous studies for this method were carried out for Ciwidey-Patuha geothermal field [4], for Ulumbu geothermal field [5], and for Arjuno-Welirang geothermal field [6]. The final objective of this study is to present the natural state model of the Cisolok-Cisukaram geothermal field, whose mass and heat flow was calibrated using the available observation data.

2. Geoscience Review
Geoscience studies have to take into account in building a natural state model. The following paragraphs describe the geology, geochemistry, geophysics, and data from existing exploration well studies based on several published papers. The previous studies in Cisolok-Cisukaram Geothermal Field were conducted by [1] [3] [7] [8] [9] [10] [11].
2.1 Geology

Cisolok-Cisukarame is composed of the morphology of hills produced by volcanic products with an attitude of 150-900 masl [11]. Cisolok-Cisukarame area is controlled by normal fault directed NE-SW and N-S acting as the main geothermal conduit. The appearance of thermal features in the Cisolok-Cisukarame area is controlled by the fault of NE-SW [12].

The geological survey conducted by Bemmelen in 1949 shows that the Cisolok area is a part of the Bayah Dome. The Bayah Dome formed by Cikotok Formation as the oldest formation. This formation is Oligocene age with units comprised of volcanic breccias, tuff, and lava deposits exposed west of Cisolok [8] Then early Miocene units consist of Citarete and Cimapag formation. The andesite and dacite intrusion of Late Miocene is exposed South of this area, as represented in Figure 2 [8].

Based on the volcano-stratigraphy map of the Cisolok-Cisukarame geothermal field shows in Figure 3, the lithology of the study area can be divided into two groups. First, groups of sediments, intrusive rocks and acidic volcanic rocks (dasite-gradionitic) as the oldest rocks in the area. The younger rock comprises intermediate volcanic rock, while the youngest deposit is the alluvium. The geology of this area is dominated by quaternary rocks of andesite and basaltic lavas and pyroclastic deposits [12].

![Geological map of Cisolok area](image-url)
Figure 3. Vulcanostratigraphy map of Cisolok-Cisukarame geothermal field [2].

2.2 Geochemistry
Geochemistry studies and analysis have been conducted in several published papers [3] [10] [1] [11]. The studies that have been conducted described that all the thermal manifestations are distributed in Cisukarame and Cisolok area, especially in the Cisolok River. The thermal manifestations are spouting spring, hot spring, and warm spring. In Cisolok area, the thermal manifestation occurs at the surface as hot spring emerging in the Cisolok River with the temperature near the boiling point (90-100⁰C) and high flow rate. The Cisolok Area is controlled by the main structure of NNE-SSW to NE-SW [12]. All the thermal manifestations in this area are controlled by a normal fault of NE-SW. The distribution of manifestation along the Cisolok River shows in Figure 4.
The thermal water has a neutral pH of about 8. Around the manifestation as in Figure 4, there is hydrothermal surface alteration dominated by silica sinter and travertine. The deposition of silica sinter in this area shows that the temperature of the fluid in the reservoir is above 200°C. Travertine alteration in the manifestations shows the evolution of this system cause the decrease of reservoir temperature and the interaction between the hydrothermal water and wall rock in this area as limestones. The type of Cisolok thermal water is HCO$_3$ water in association with Cl water; it causes the rock type in the Cisolok area is limestone.

The previous study of geochemistry and analysis described the distribution of manifestations around the Cisukarame area [1]. The manifestations of this area consist of hot springs, warm spring, and hot pool above andesite rocks in Cisukarame River. The temperature of manifestations approximately between 54-99°C with pH between 6.8-8.2. Another geothermal manifestation of Cisukarame located about 6 km north of Cisolok manifestation [3]. The manifestation is hot pools with temperature about 46°C and pH about 7.7 with a very low flow rate. The type and characteristic of the manifestation fluids are similar to the manifestation in Cisolok. The major anion of the fluid is HCO$_3$ and the major cation is Na. HCO$_3$ water resulted in condensation of steam into groundwater, and surface water in the Cisukarame area indicates that Cisukarame area is an upflow zone. The chemical composition thermal water in Cisukarame and Cisolok area indicates that the deep thermal water will flow laterally to Cisolok, but the steam will discharge directly up to Cisukarame. The type of water in Cisolok-Cisukarame is shown in Figure 5 based on manifestation water in Cisolok and Cisukarame Area.
Figure 5. Composition of Cl-SO\textsubscript{4}-HCO\textsubscript{3} of Cisolok-Cisukarame hot spring. Point 01 and 07 for manifestation in Cisolok and CRM is sample from Cisukarame [3].

Figure 6. Na-K-Mg diagram of Cisukarame manifestations [1].

The reservoir temperature in the Cisolok area is determined by using Na-K geothermometer. The result of geothermometer analysis shows that the reservoir temperature in Cisolok area is 190-200°C and decreasing until 170°C using Na-K-Ca geothermometer [12]. The decreasing temperature of the reservoir affects the characteristic and mineralogy of surface alteration deposits from silica sinter to travertine deposits. In Cisukarame area, the calculated reservoir temperature was conducted, and the reservoir temperature is determined by using Na-K geothermometer with empirical equations derived from the theory by [13], and [14] shows in Figure 6 [1]. The range of temperature in this area is about 185-212°C. Based on the result of reservoir temperature, Cisolok-Cisukarame geothermal system can be categorized as a medium enthalpy geothermal system [15].

Based on isotope analysis conducted by and the water in the Cisolok-Cisukarame area located near the local meteoric water line as shown in Figure 7 [11]. The water of the reservoir is interpreted to be derived from meteoric water. The geothermal system in this area identified as an old system based on the presence of meteoric water in the reservoir. The similarity of the isotope content states that the
meteoric water in the reservoir comes from run off of the fluid in the same region which is controlled by the geological structure as recharge area.

![Kurva Isotop δ deuterium vs δ 18O](image)

**Figure 7.** Correlation curve of O and H [11].

2.3 Geophysics

The geophysical study has been done by using the Magnetotelluric (MT) and DC resistivity method. From the MT method, it indicated that the prospect area is in between Cisolok and Cisukarame as shown in Figure 8.

The geophysical study indicates that the low resistivity layer can be found below the Cisolok-Cisukarame area and distributed in the direction of NE-SW in the east area. This low resistivity layer can be interpreted as a caprock layer from the Cisolok-Cisukarame geothermal field. Magnetotelluric (MT) cross-sections are southwest-northeast (line 02) and northwest-southeast (line 24), depicting the tentative model of Cisolok-Cisukarame system indicated by conductive layers and heat sources as we can see at Figures 9 and 10. The pattern of dispersion of the conductive layer is identified in the east with the relative direction of the southwest-northeast. MT data shows that the caprock is located in Cisukarame area and has a BOC at a depth of 400m. The heat source is estimated to be located in NE of Cisolok Cisukarame area.
Figure 8. The prospect area in Cisolok-Cisukarame [2].

Figure 9. Magnetotelluric result of line 02 (SW-NE) of Cisolok-Cisukarame [2].
Figure 10. Magnetotelluric result of line 24 (NW-SE) of Cisolok-Cisukarame [2].

The DC-Resistivity survey with the Schlumberger electrode configuration shows an anomaly low resistivity <10 Ohm and also shows an elongated contour pattern and open to the southwest. This pattern when found on topographic highs, which then sloped usually reflects an outflow [16]. Resistivity survey of [16] indicates that the Cisolok area is an outflow zone because of the low resistivity value along the Cisolok River. The study also indicates that the Cisolok and Cisukarame comprise one geothermal system.

2.4 Well Data
One exploration well was drilled in the Cisolok-Cisukarame area to reach the temperature distribution in this area. This exploration, well namely CSL-01 was drilled by Pertamina in 1986. CSL-1 has a total depth 1,477.36 m, but the reservoir condition is not described in this well cause the well does not reach the reservoir. CSL-01 is situated in Pasir Pameungpeuk, Cisolok, around 300 m from Sungai Cipanas hot spring and 2 km from Desa Cisolok. CSL-01 representing the temperature distribution in the outflow zone. The distribution of temperature in CSL-01 and the data of the well shows in Table 1.
Table 1. The Well data of CSL-01, Cisolok [10].

| Well Name                  | CSL-01                  |
|----------------------------|-------------------------|
| Well Location              | Pasir Pameungpeuk, Cisolok |
| Well Depth (m)             | 1,477.36                |
| Temperatur Max (°C)        | 107                     |
| Significant Rock Found     | Limestone               |
| Partial Loss Circulation   |                         |
| Depth (m)                  | 540-570 m               |
|                           | 1148 m                  |
| Total Loss Circulation     |                         |
| Depth (m)                  | 317 m                   |
|                           | 719 m                   |

2.5 Initial Conceptual Model

The initial conceptual model is shown in Figure 11 [2]. The conceptual model was built from the geoscience data in the Cisolok-Cisukarame area. Upflow zone in this system located near Gunung Talaga or in Gunung Halimun based on the distribution of geophysics and geochemistry data when the outflow zone located in Cisolok area. The fluid of this system moving laterally from Gunung Halimun to Cisolok area controlled by main structure directed NE-SW. Heat source of this system is by volcanic activity below the Gunung Halimun. Cisolok-Cisukarame is a liquid dominated system with the temperature of the reservoir is about 180-200°C. However, the accuracy of the model is not valid enough because of unavailable data in Gunung Halimun as an up-flow zone. It is hoped that the new geoscience data and the result of numerical modeling would give new input to create a better conceptual model that represents the heat and mass flow in this system.

Figure 11. Conceptual model of Cisolok-Cisukarame geothermal system [2].
3. Natural State Model

3.1 Model Structure
The EOS 1 for water and water with tracer is used in the model to simplify the modeling process. The areal extent of the modeled area is about 90 km², it covers the reservoir, well, and the recharge-discharge area. The model consists of 12 layers with some of the top layers follow the real topographical condition, the vertical extent of the model is 3.3 km. Figure 12 indicates the plan view of the model gridding system. The faults were also included in the model by applying the internal boundary structures.

![Gridding and layering system.](image)

Figure 12. Gridding and layering system.

The model was divided into 11,232 active grid blocks by using a rectangular grid type with various sizes depending on the geological condition. The grid block horizontal dimension varies from the smallest 250×250 m to the most significant 1100×1100 m. The model is divided into 13 layers; each layer is 200 m thick, except for layers 12 & 13 which are 400 m thick. NE-SW faults are prominent in the area, and they are most likely to be the main conduit of the system, the model was rotated in the same direction as those faults.

3.2 Initial and Boundary Conditions
The following initial and boundary condition was defined to simulate the reservoir. At the initial condition, the pressure and temperature of 1 bar 25°C were applied to the system. The top boundary layer was set to be constant at atmospheric conditions, while the side boundary was assumed to be no flow boundary and was treated to be relatively impermeable. Hot water with constant enthalpy and the mass rate is injected into the Cisolok area base (Figure 13) to represent a deep heat flow into the system. The amount of the deep up-flow recharge obtained from initial state calibration was 31.4 kg/s at an enthalpy of 1450 kJ/kg, and the amount of the deep injection recharge obtained from the initial state calibration was 5 kg/s at an enthalpy of 1000 kJ/kg.
3.3 Surface Injection
To simulate the rain infiltration, the surface injection was added based on annual rainfall data of Sukabumi District of 2,594 mm/year with the 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.

3.4 Rock Properties
In natural state modeling, the permeability structure is the most critical parameter, and it was continuously adjusted until the natural state condition was achieved. This effort could be carried out by hundreds of trial and error attempts. The material distribution of the model and its value for each material shows in Figure 14.

3.5 Natural State Modeling Result
In achieving the natural state condition, the model was run until the steady-state condition was reached. The modeling result was then compared to the actual data in terms of well temperature and manifestation.
mass rate. There is only one observation well available to match the model, and it is obtained from CSL-01. The dummy well in Cisukarame area was also used to match the reservoir temperature by using Na-K-Mg geothermometer. The Cisolok and Cisukarame hot springs were used to match the manifestations mass rate. The natural state condition was achieved by adjusting the permeability structure and the productivity index of the wells representing the manifestations. On the other hand, the amount of the deep up-flow recharge and enthalpy were also adjusted.

Figure 15. CSL-01 temperature matching.

Figure 16. CKR-D temperature matching.

The modeling process was carried out by using TOUGH2. Figure 15 indicates the temperature matching of CSL-01. It shows a very good match between the actual and the modeled temperature.

From the pressure and temperature profiles above, it can be inferred that the reservoir is a water dominated reservoir. The pressure shows the nearly hydrostatic profile, and the temperature profile falls below the boiling point with depth curve. This well is located on the outflow zone of the geothermal reservoir and is encountering low permeability rocks, and it has a maximum temperature of 119°C at the lowest part of the well.

Figure 16 indicates the temperature profile of a dummy well CKR-D located in the Cisukarame area. This well is used to match the reservoir temperature in the Cisukarame area based on Na-K-Mg temperature.

Figure 17 shows the vertical slicing, and Figure 18 shows the horizontal slicing of the temperature profile of the Cisolok-Cisukarame geothermal system. The up-flow zone of the system is located in Cisukarame area while the outflow zone, towards the southeast in Cisolok area.

Furthermore, the hot springs in Cisolok and Cisukarame areas have been successfully represented by dummy wells with a certain amount of mass out of the model. The representation was done by producing the dummy wells at an atmospheric pressure condition to reach the total amount of mass rate of about 68 kg/s and 9 kg/s from Cisukarame and Cisolok area, respectively. This attempt was made by adjusting the productivity index value of those dummy wells. It is gained that the productivity index in the Cisukarame hot spring is about 9.55×10^{-13} m³ while in the Cisolok hot spring is 1.13×10^{-13} m³.
4. Natural State Model
The data were integrated to build a comprehensive conceptual model of Cisolok-Cisukarame. The NE-SW oriented horizontal cross-section of the Cisolok-Cisukarame area followed by a vertical section directed SW-NE of Cisolok Cisukarame conceptual model illustrated in Figure 19. The fluids flow are taken from the geochemistry of Cisolok water that indicates that the water flows laterally from a deep geothermal reservoir; in contrast, the Cisukarame thermal water is an up-flow of HCO₃ water resulted by condensation of steam into groundwater and surface water. The heat source is located below Cisukarame area according to the geochemistry data of the surface manifestations and the geophysics data shows the location of the caprock of this system. The distribution of temperatures is taken from the numerical model that has been built in TOUGH2.
Figure 19. Updated conceptual model of Cisolok-Cisukarame.

5. Conclusion
The natural state model of the Cisolok-Cisukarame geothermal field has been successfully developed and validated by using the observation data. The new conceptual model has been achieved by integrated geoscience data and numerical modeling results. Cisolok-Cisukarame is a liquid dominated geothermal system with up-flow zone in Cisukarame area not in Gunung Talaga or Gunung Halimun area. The fluid flow from the upflow zone in Cisukarame area to outflow zone in Cisolok area. The temperature of the reservoir is about 185-212°C with intrusion below the Cisolok-Cisukarame area as the heat source of this system.

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