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Dynamic Numerical Simulation for Sustainability of Geothermal Reservoirs: an Enhanced Model of Patuha Geothermal Field

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ABSTRACT

In recent years, numerical simulation has emerged as a cornerstone practice within the geothermal industry. Using numerical reservoir simulation, we can comprehend and manage the complex dynamics of geothermal reservoirs. The Patuha geothermal field, a vapor-dominated geothermal reservoir located in West Java, Indonesia, was developed by PT. Geo Dipa Energi (Persero) has maintained an installed capacity of 60 MW since 2014. The numerical model of the Patuha geothermal field was developed in 2013 and subsequently updated in 2019. A new and enhanced numerical model has been developed to assess the reservoir changes resulting from fluid extraction within the reservoir. Compared with the previous model, this enhanced numerical model incorporates additional geoscience surveys, an updated conceptual model, thorough PT shut-in data analysis, and data from newly drilled wells. The reservoir simulation results, validated with the natural state and history matching calibration, provide a deeper understanding of the reservoir's condition and resources. This understanding aids in identifying and mitigating potential risks associated with reservoir extraction. Furthermore, this information is the foundation for short-term and long-term future development strategies, including production and injection strategies for the Patuha geothermal field.

1. INTRODUCTION

The Patuha geothermal field, situated in the Pangalengan geothermal working area approximately 50 km from Bandung, West Java, as depicted in Figure 1, is a vapor-dominated geothermal reservoir. Since September 2014, the field has been providing electricity to meet the demand in Java-Bali through the operation of a 60 MW capacity power plant. Initially, the development of Unit 1 at the Patuha geothermal field involved the installation of 17 temperature core hole wells, defining the specified area of interest. These wells, drilled in 1996 by Patuha Power Limited, were accompanied by 2 injection wells and 12 production wells for injection and production purposes during the initial development stage.

As a means to maintain production sustainability and support the development of the reservoir, the Patuha geothermal field's numerical model has been previously established in research conducted by West JEC (2007), ELC (2013), Schotanus (2013), Firdaus et al. (2016), and Ashat et al. (2019). However, the extraction of the fluids from the reservoir leads to a change in the reservoir condition, prompting the need for an updated and comprehensive numerical model. Continuous adjustments to the numerical model are imperative to reflect the Patuha geothermal reservoir's dynamic nature accurately. The process involves updating the model in response to changes induced by fluid extraction, incorporating the latest geoscience data, and ensuring alignment with the evolving conceptual model of the Patuha geothermal field. In contrast to the prior numerical model, this improved model is adjusted using the latest PT shut-in data and recent pressure and enthalpy data encompassing all production wells and incorporates a dual porosity approach. In this research, Patuha's enhanced dynamic numerical model focuses on assessing the reservoir condition and provides insights into determining the development strategy.

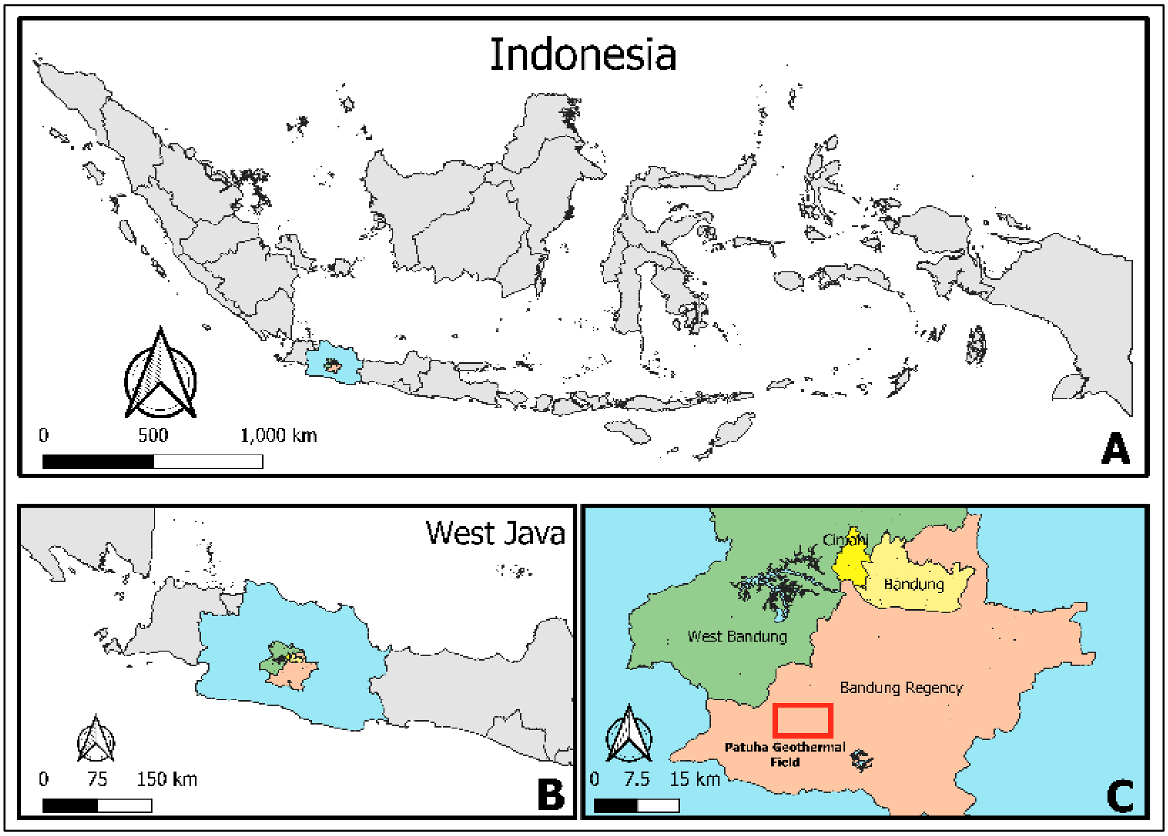

Figure 1: Patuha geothermal field location.

2. CONCEPTUAL MODEL

The conceptual model of a geothermal field plays a vital role in the effective development and utilization of geothermal resources. In the case of the Patuha geothermal field, along with the additional geoscience activities conducted in the Patuha geothermal field, such as geochemical survey and sampling, geological mapping, geophysical data acquisition, and recent well data, the updated conceptual model of the Patuha geothermal field has been developed by integrating all these data. The updated conceptual model is intended to enhance comprehension and information regarding the reservoir condition of the Patuha geothermal field after 9 years of production.

The geological study reveals that the Patuha reservoir's caprock consists of clay minerals (smectite and kaolinite) resulting from argillic alteration from shallow deep until the elevation of 1.500 – 1.200 masl. The 3D inversion of Magnetotelluric (MT) data indicates a northwest-to-southeast extension of the caprock, identified by a low resistivity anomaly (<10 ohm-meter) at a thickness ranging from 750 to 2,500 meters. The top reservoir, estimated at 1,100 – 1,329 masl based on static Pressure-Temperature (PT) data, exhibits a 217 – 238 ºC temperature range. Reservoir rocks predominantly feature rough pyroclastic lithology and andesite lava, with occasional diorite/micro diorite intrusions. The MEQ data and insights from the deepest production well suggest that the bottom of the reservoir is situated between -350 and -750 masl. The heat source for the reservoir is associated with Mt. Patuha Utara, Mt. Patuha Selatan, and Mt. Urug, with the 3D gravity model indicating magma intrusion beneath these mountains.

The hydrological pattern of the Patuha geothermal field consists of an upflow zone, outflow zone, marginal, and recharge zone. The upflow zone in the Kawah Putih and near Mt. Urug area is indicated by chloride-sulfate water manifestation and high H_2S content from well samples. In comparison, the *outflow* zone is located in the northwest part of the reservoir, indicated by the HCO_3 and peripheral water, without any indication of steam feature manifestation. The marginal zone of the reservoir is indicated by the emergence of Ciwidey fumarole, which has NH_3 chemistry characteristics. The reservoir's recharge zone is identified in the southeastern part of the field. This updated conceptual model forms a foundation for the comprehensive understanding of the Patuha geothermal reservoir's dynamics, aiding in sustainable resource management.

3. UPDATED DYNAMIC NUMERICAL MODEL

By incorporating the latest PT shut-in data, recent pressure and production enthalpy information, and a dual porosity approach, the numerical model aims to provide a dynamic framework for assessing reservoir conditions and formulating optimal development strategies. The numerical model of the Patuha geothermal field is built on the TOUGH2 simulator. Without ignoring the essential parameters, the equation of state (EOS) used in the model is EOS1 to simplify the simulation process.

3.1 Numerical Model

Based on the area delineation, the numerical model has a total area of 159 km^2, covering the X and Y axis with lengths of 13.8 km and 11.5 km for each axis. The model was oriented to 344º direction to fit the orientation of the faults and cross-section of the conceptual model. Compared with the previous model, the actual topography data is applied in this model, as shown in Figure 2. Each grid block in the numerical model is applied to represent the interaction and phenomena between the fluid and the rock in the reservoir. The grid block used in the numerical model is rectangular, with sizes varying from 100 × 200 m to 1.150 × 1.150 m. Specifically for the interest area, the grid block used is 100 × 200 m and 200 × 200 m, with a total area of interest of 49.68 km2 (Figure 3). The numerical model of Patuha comprises 5 main layers: the atmosphere, groundwater, cap rock, reservoir, and basement. Figure 4 presents the layer division on the numerical model. The caprock, reservoir, and basement layers are divided into sublayers, with the total of the layers in the numerical model being 19 layers.

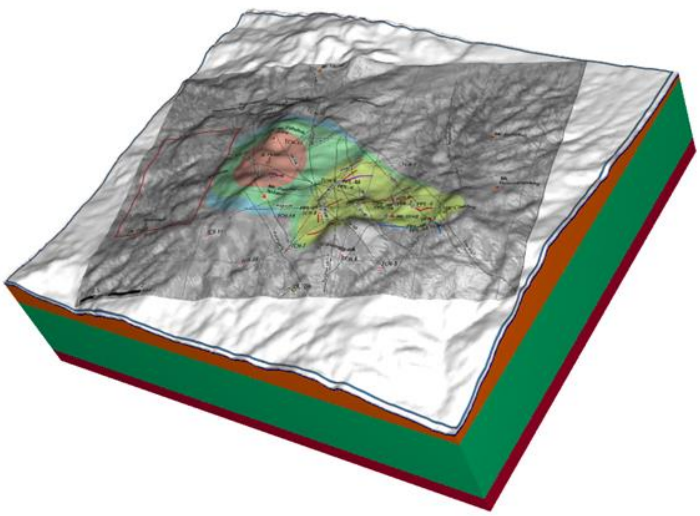

Figure 2: 3D visualization of the numerical model.

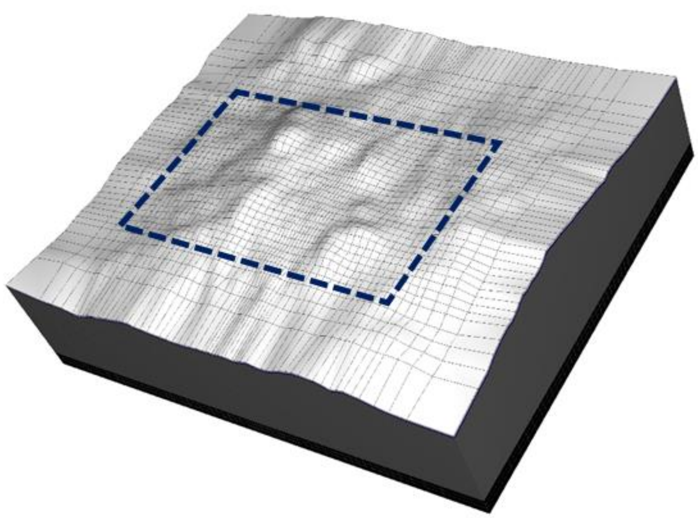

Figure 3: Grid block and interest area.

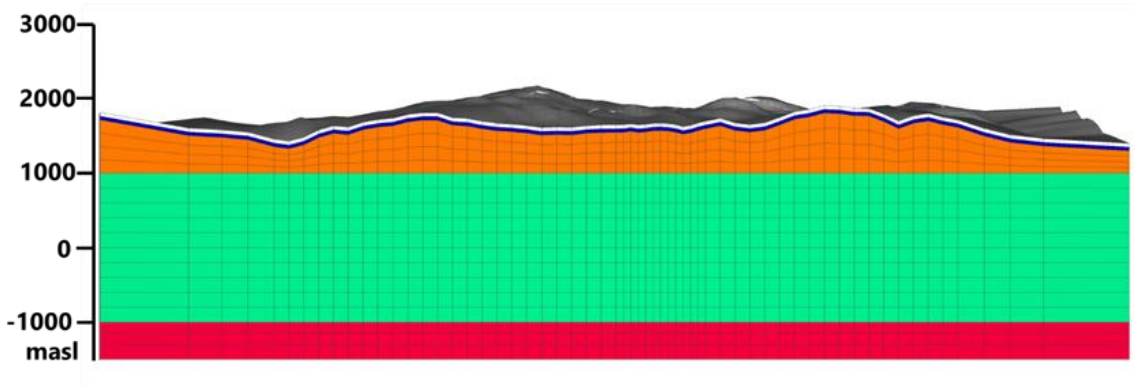

Figure 4: Layer distribution.

The general parameters of the dual porosity numerical model, such as matrix permeability, matrix porosity, fracture spacing, and fracture volume fraction defined in the model, are 0.01 mD, 10%, 50 m, and 5%. Furthermore, apart from the general parameters, the physical parameters of each rock assigned to the grid block, namely the density, wet heat conductivity, and specific heat, are specified at 2600 kg/m^3, 2 W/(m.K), and 1 kJ/(kg.K). Moreover, the numerical model calculations applied the relative permeability with Grant's curve and capillary pressure with a linear equation.

3.2 Input Material

The dual-porosity model consists of a network series of fractures and grid blocks, where fractures are interconnected in three dimensions, allowing the rock matrix to fully connect to fractures and partially connect to adjacent matrix grid blocks (Ashat et al., 2019). The matrix grid blocks have a much larger volume but very low permeability and act as storage units for fluid in the field. In general, the reservoir fluid movement mainly occurs through the fracture network (Pruess, 1999). The material's properties in the numerical model play a crucial role, particularly during the natural state calibration (Keintjem et al., 2023). Using the dual porosity approach, the total grid block of the updated numerical model of Patuha reached 44460 grid blocks.

The boundary conditions are divided into 3 parts: top boundary, bottom boundary, and side boundary. The top boundary is set at constant conditions with a pressure of 1 bar and a temperature of 25 degrees C. At the bottom boundary, pressure and temperature conditions are set to 160 bar and 240 degrees C within the reservoir area and 340 bar and 140 degrees C outside the reservoir area. The rock material is set to impermeable conditions for the side boundary with a fracture permeability value of 1×10^{-20} m^2.

The heat source in the Patuha system is estimated to originate from two heat sources: the primary heat source in the Kawah Putih area and a secondary heat source in the Urug Utara area. The heat source is modeled by injecting hot water with constant enthalpy and flow rate at 2000 – 2300 kJ/kg and 52 – 120 kg/s. Calibration is also carried out by referring to the manifestation of the Patuha system by adding a dummy well to represent the natural discharge manifestation. These wells are set to production conditions and constant pressure on well deliverability. The location of the recharge and discharge of the Patuha geothermal system is shown in Figure 5.

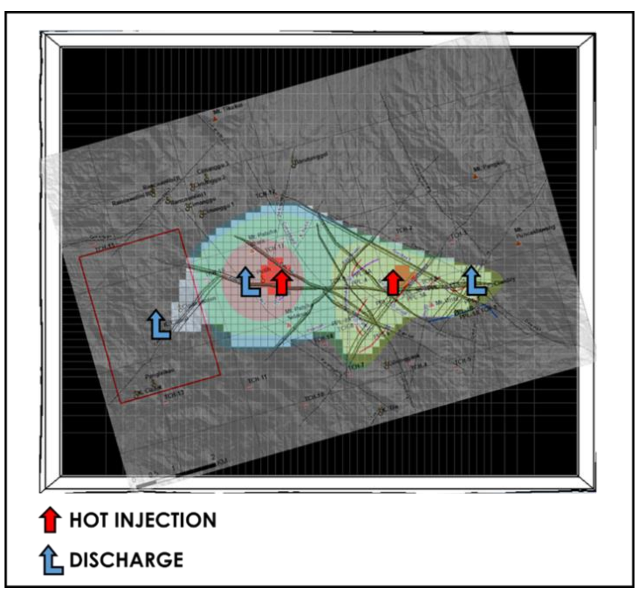

Figure 5: Recharge and discharge location.

In the natural state calibration stage, the rock property that has the most significant impact is the permeability of the reservoir rock. The permeability of the rock affects the distribution of the pressure and temperature in the reservoir model, as well as the fluid flow within the reservoir. The rock permeability in the x, y, and z directions is a crucial rock parameter calibrated to align the numerical model with the actual conditions. In the dual porosity approach, fracture permeability is pivotal in the model's distribution of pressure and temperature, as well as fluid flow distribution. A cross-section of the material distribution of the numerical model is shown in Figure 6. Once a satisfactory match is achieved, it is assumed that the model accurately represents the permeability distribution in the reservoir. Detailed parameters of each material used in the numerical model are summarized in Table 1.

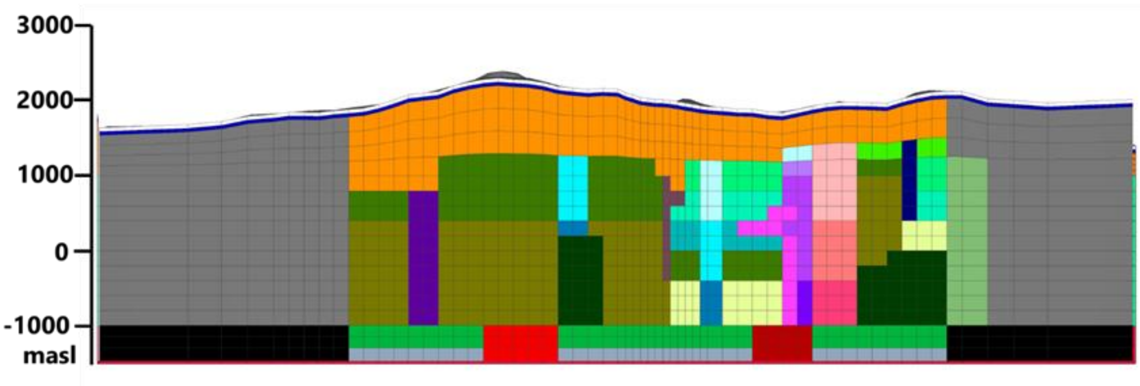

Figure 6: Vertical section of the material distribution.

Table 1: Material properties of reservoir rocks.

Color	Material	K_{xy} (mD)	K_z (mD)
	CAP	0.001	
	DIOR	0.01	
	HET	50	100
	BASE	0.001	
	BRES		
	BOUN	0.00001	
	RES1	90	45
	RES2	80	40
	RES3	70	35
	RES4	30	15
	RES5	20	10
	FLT1	35 – 100	
	FLT2	30 – 80	
	FLT3	20 – 60	
	TIIS	0.01	
	SGH2	0.01	

The assigned material for the top of the reservoir and the top of the cap rock are based on the updated conceptual model of the Patuha geothermal field. The reservoir material used has a permeability range of 1 – 90 mD. Meanwhile, the fault parameters range in a 0.01 – 100 mD permeability value. The rock permeability is set under anisotropic conditions, where the permeability in the z direction is smaller than in the x and y directions. Meanwhile, some faults with very low permeability are assumed to act as seals controlling the pressure and temperature distribution in the model. Two faults act as seals, namely the Sugihmukti 2 and Tiis faults. Sugihmukti 2 fault is set from an elevation of -400 (masl) to the top of the reservoir (ToR) area, while the Tiis fault is set at elevations ranging from 400 masl to 1450 masl in the ToR area.

4. NUMERICAL MODEL RESULT

The reservoir numerical model simulation employs three fundamental procedures to comprehend and assess reservoir conditions: natural state calibration, history matching, and forecasting. The natural state constitutes the initial phase of the numerical model calibration process. If the natural state calibration result reasonably aligns with the actual PT data, the model outcomes serve as the basis for history matching. In the history matching phase, the model's output is calibrated to match the production data, encompassing parameters like enthalpy and pressure. After the history matching calibration is completed, the next step to evaluate the sustainability of the reservoir is forecasting based on the company's development strategy, which includes consideration for production and injection strategies.

4.1 Natural State

Natural state simulations were conducted by running the model to an extensive simulation time to reach a steady-state condition. Since the numerical model of the Patuha geothermal field used the dual porosity approach, the simulation time is set to 100,000 years to reduce the calculation process. The model was run with adjusted simulation time without any production or injection. In this stage of the numerical model, the PT data in the numerical model is validated against the actual PT data. The natural state calibration is carried out through several iteration steps to reach a suitable match between the PT result from the model and actual PT data. The iteration process includes adjusting reservoir rock material distribution and rock permeability values, determining the enthalpy value and mass injection at the heat source, adjusting the location of upflow and recharge, and refining the grid block size.

The results of QC data logging under shut-in conditions indicate that not all wells are stable. As shown in Figure 7, from 14 production and injection wells, there are 2 wells in unstable conditions, 3 wells in partially stable conditions, and 9 wells in stable/high confident conditions. Hence, the validation of the PT data from the model emphasizes on well with a higher level of confidence.

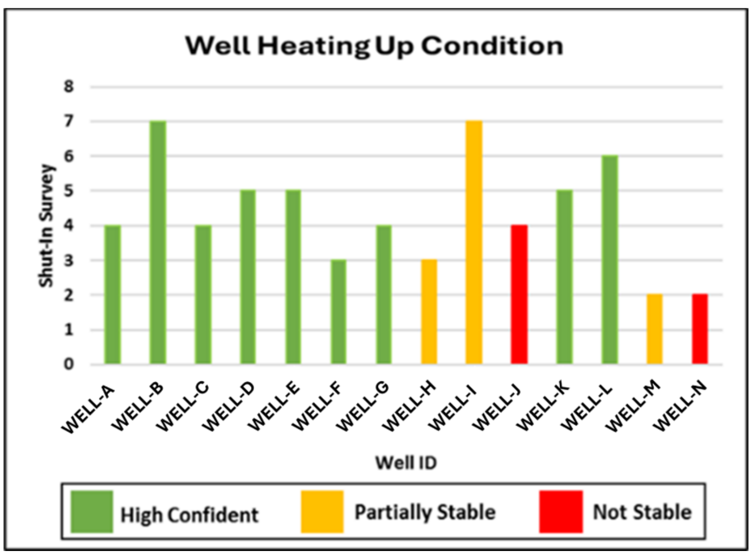

Figure 2: Well heating-up QC result.

As summarized in Figure 8, the natural state results adequately fit the actual PT shut-in data. The pressure exhibits a stable pattern and convective temperature trend, signifying the reservoir is vapor-dominated with high permeability rocks. Nevertheless, the presence of a liquid zone within the reservoir is apparent in the pressure trend, aligning with hydrostatic pressure characteristics observed in the wells WELL-B, WELL-C, WELL-D, and WELL-L. Based on the PT data of those wells, the liquid zone is indicated below 500 masl. However, among the four wells indicated to have a liquid zone in the reservoir, only one is located in the central area of the reservoir, whereas the remaining three wells have trajectories to the peripheral area of the Patuha reservoir delineation. Therefore, further study and thorough exploration are necessary to understand the Patuha reservoir's liquid zone.

Based on the PT matching result, three pressure zones existed in the Patuha reservoir. A high-pressure area exists near WELL-I, a moderate pressure in the center of the reservoir near the central production zone, and a low-pressure area in the western part of the reservoir (Figure 9). The pressure values of the high, moderate, and low pressure areas are around 47 bar, 28 bar, and 18 bar, respectively. The temperature distribution on the natural state of the Patuha geothermal field based on the numerical model results is shown in Figure 10. The heat and mass flow of the reservoir come from beneath the Kawah Putih and Urug area. The high temperature occurred in the reservoir's center area and then began to decline to the western area below Kawah Ciwidey.

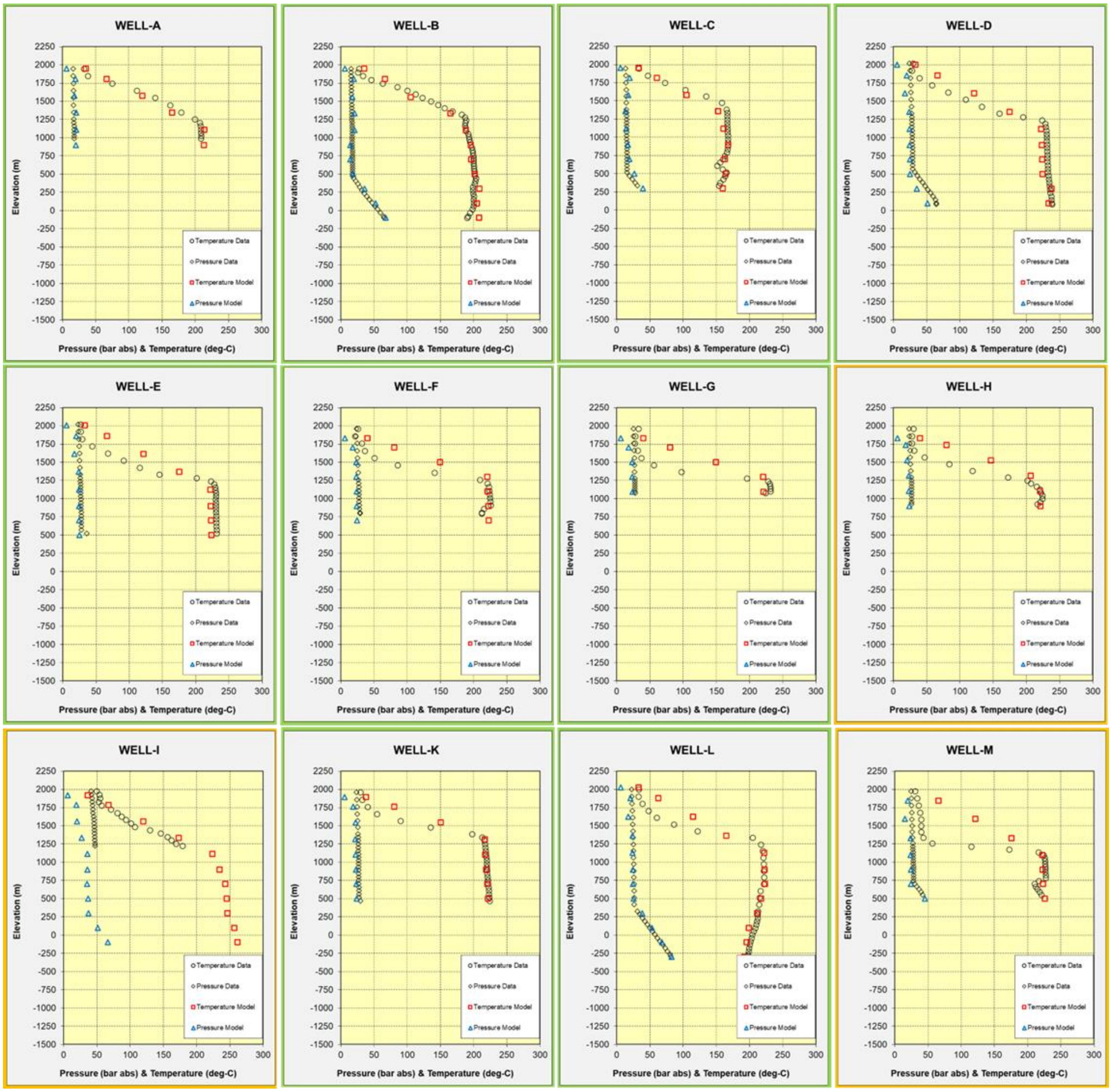

Figure 3: PT matching result.

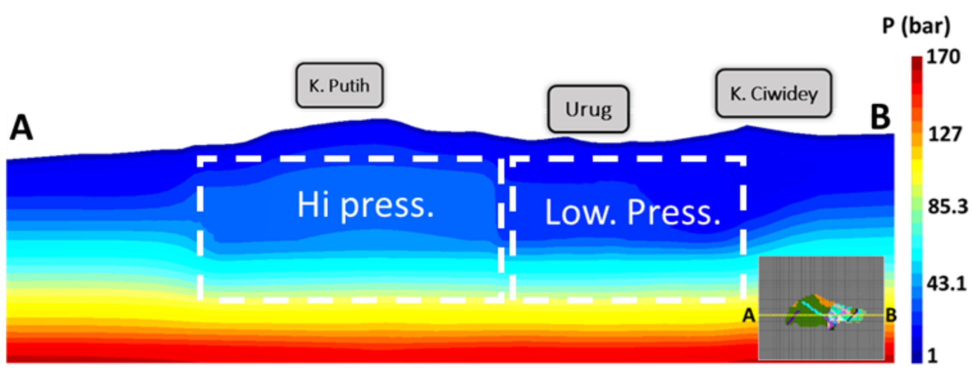

Figure 4: Pressure distribution in the 3D model.

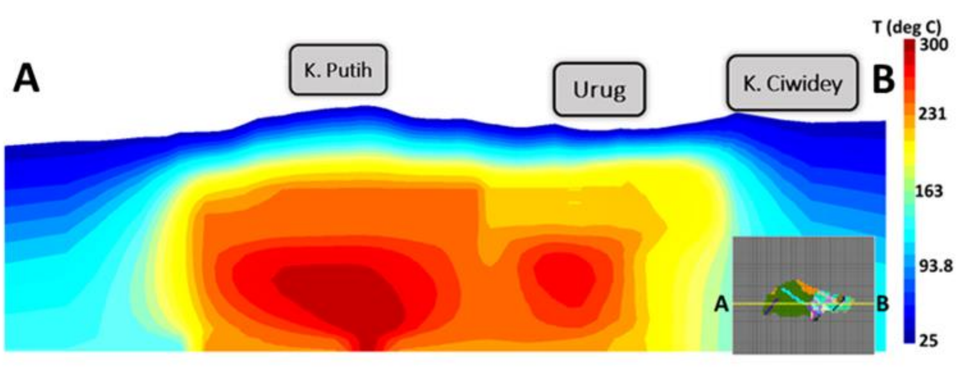

Figure 5: Temperature distribution in the 3D model.

4.2 History Matching

At the history matching stage, the results of the numerical model simulation aligned with actual production data from each production well in the Patuha geothermal field. The model used in the history matching process is a natural state calibration model that has achieved conformity with the actual well pressure and temperature data. In the history matching calibration of the Patuha field, the model aligned with production and injection data for approximately 8 years since COD in 2014. Pressure results are validated based on the shut-in production and Wellhead Pressure (WHP) shut-in data. Meanwhile, based on the availability of data, not all production wells have shut-in production and shut-in WHP data. Therefore, the history matching calibration is only performed using the data from wells with complete shut-in production and WHP shut-in data.

The enthalpy of each well in the numerical model is aligned with the actual enthalpy data from the production wells. In an isenthalpic condition, the fluid enthalpy in the wellbore is equal to the fluid enthalpy in the surface. The fluid enthalpy in wells with significant dryness value is validated with the enthalpy value on the surface. Conversely, for the wells with dryness values that tend to be smaller than production wells or indicated as two-phase fluid production, enthalpy data from TFT is used as the basis for enthalpy in history matching calibration. The result of the history matching calibration of the Patuha geothermal field is shown in Figures 11 and 12.

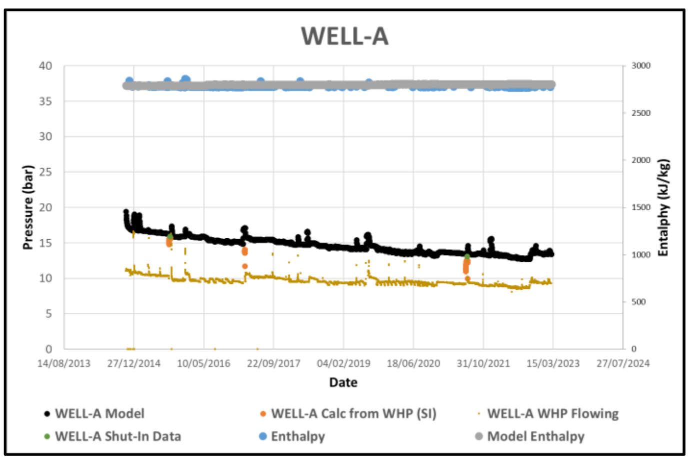

Figure 6: History matching calibration results for low pressure well.

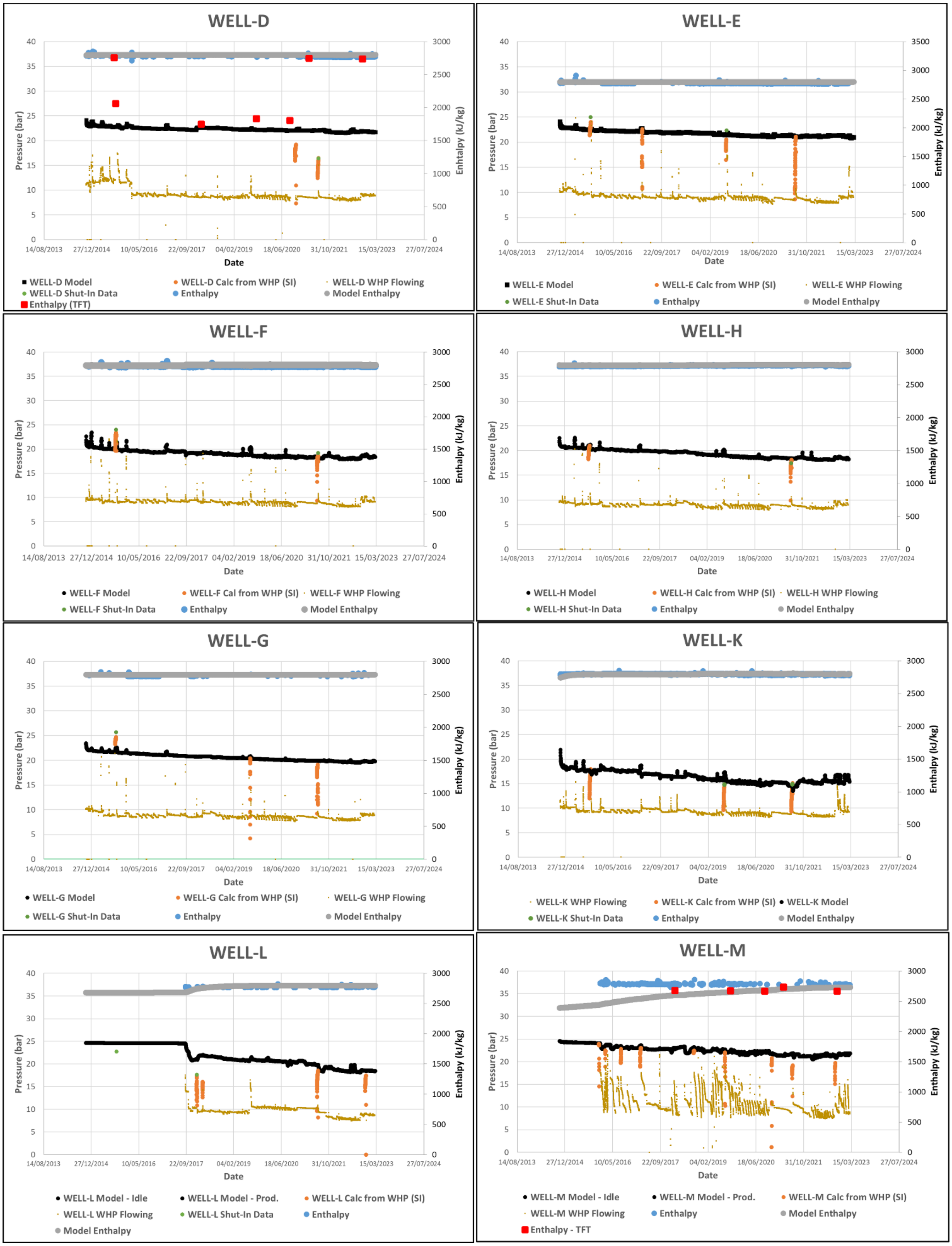

Figure 7: History matching calibration results for moderate pressure wells.

Based on the history matching calibration results, the model's pressure and enthalpy aligned with the actual production pressure and enthalpy data of the Patuha geothermal field, particularly the production well. The enthalpy values of the wells during production indicate an increase, specifically in WELL-A, WELL-F, WELL-H, and WELL-K. These wells produce single-phase steam to supply the power plant's demand. These wells' enthalpy values are nearly 2800 kJ/kg, indicating a superheated condition in the respective well areas. In contrast to the previous wells, two wells, namely WELL-D and WELL-M, produce two-phase fluids. In the case of well WELL-D, the production of the two-phase fluids is evident from the enthalpy trend based on the TFT. Based on the TFT, the enthalpy value from initial production has decreased by approximately more than 500 kJ/kg. The decrease in the enthalpy value is attributed to well leakage, leading to the intrusion of cold meteoric water into the well, contributing to fluid production during the operation. Meanwhile, in WELL-M, the production of a two-phase liquid, which can be seen on the enthalpy from TFT, results from the condensate layer in the area of WELL-M.

Extracting fluids from the reservoir and injecting fluids into the reservoir leads to changes in the reservoir properties, such as temperature, pressure, and steam saturation. The decrease in pressure and the increase in steam saturation in the reservoir are markedly influenced by the mass of fluid extracted from the reservoir. The increase in steam saturation in the reservoir correlates directly with the quantity of fluid extracted, while a larger volume of extracted fluid results in a more significant decrease in reservoir pressure. The outcome of history matching calibration allows for describing changes in the reservoir through the numerical model.

The temperature changes within the reservoir during production are illustrated in Figure 13, which compares the reservoir condition in the natural state and after the history matching calibration results. The temperature decreases in the range of 5 – 9 ºC occurred in the eastern and southern areas of the Patuha reservoir, where the production wells are situated. In line with the decrease in temperature, the pressure also decreases in the production area of the Patuha reservoir. As illustrated in Figure 14, the pressure decreases in the range of 1.8 – 6.5 bar.

Over time, fluid extraction from the reservoir increases steam saturation and decreases the temperature and pressure. According to the natural state calibration results before production, the maximum steam saturation in the Patuha reservoir is 78%. During the eight years of production from 2014 to 2023, a significant increase in steam saturation occurred, particularly in the production area, reaching up to 100%. The high increase in steam saturation occurred in the areas of WELL-A, WELL-F, WELL-H, and WELL-K, which is in line with the increase in the enthalpy value of those wells (Figure 15). The production wells in this area yield the highest amount of steam compared to the production wells in other areas.

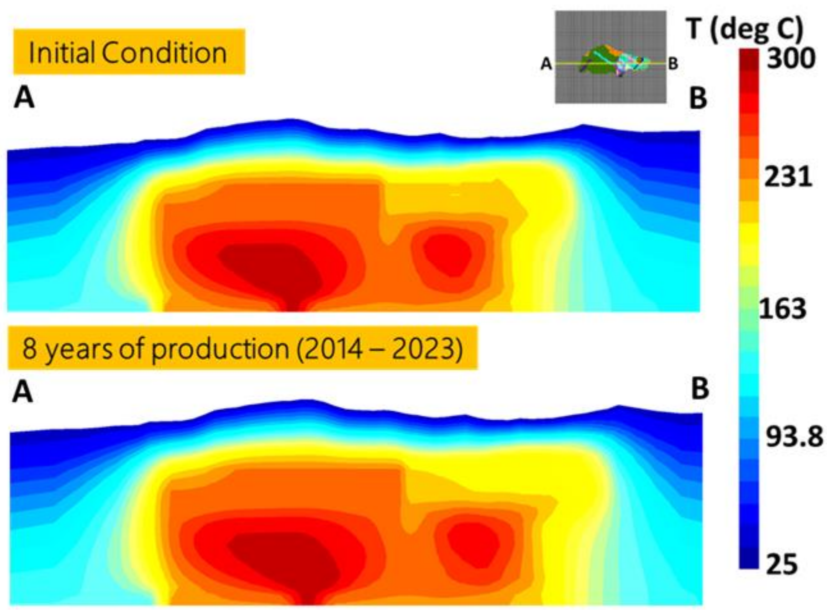

Figure 8: Temperature distribution comparison.

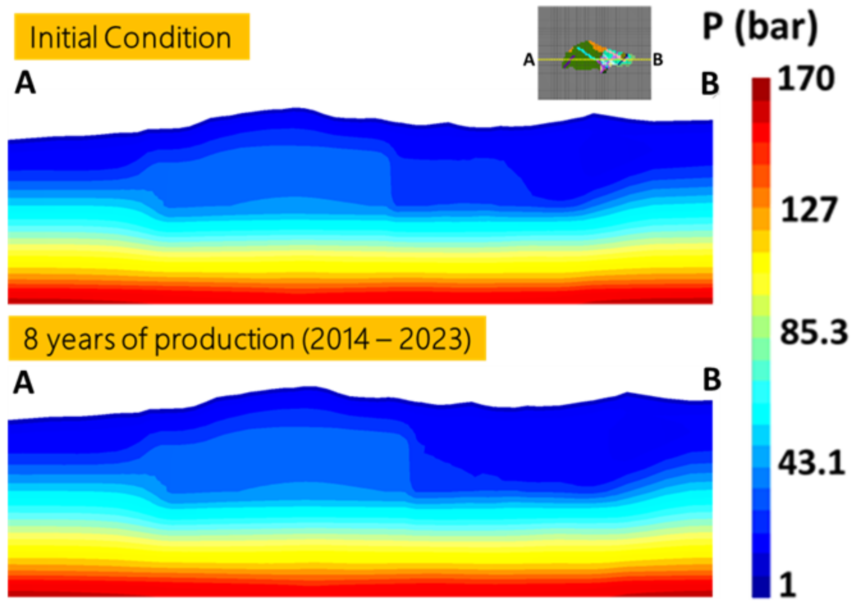

Figure 9: Pressure distribution comparison.

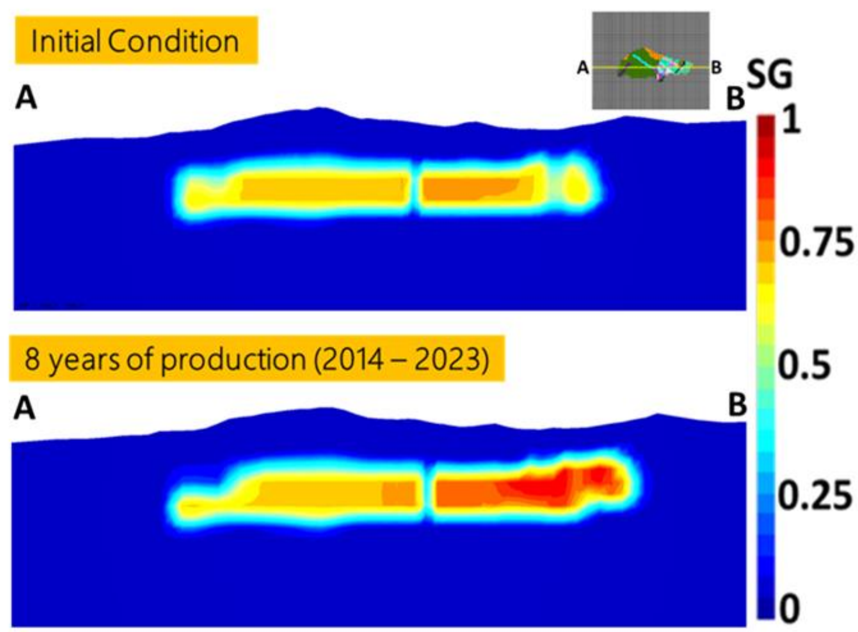

Figure 10: Steam saturation comparison.

5. CONCLUSION

The updated numerical model of the Patuha geothermal field is successfully developed based on the updated conceptual model. Using a dual porosity approach, detailed parameters, and boundary conditions, the numerical model demonstrates good alignment with the actual data through calibration in natural state conditions and history matching. Based on the natural state calibration, the Patuha reservoir is a vapor-dominated reservoir with high permeability rocks. The reservoir area is divided into three different pressure regimes: the high pressure area beneath the Kawah Putih, the moderate area beneath the Urug area, and the low pressure area beneath the Kawah Ciwidey area. However, a liquid zone within the reservoir is noted, requiring further exploration and analysis. The history matching calibration, validated against the actual production data, highlights the pressure and enthalpy changes that occur in the reservoir. The increase in enthalpy and steam saturation, particularly in wells producing single-phase steam, signifies a superheated condition. Therefore, to ensure the sustainability of the reservoir of the Patuha geothermal field, it is imperative to formulate the resource management strategy based on the result provided by the updated numerical model, with a specific focus on the regions exhibiting superheat conditions. Some strategies required to maintain the sustainability of the Patuha geothermal field may include actions such as drilling makeup wells, establishing additional reinjection wells, and other measures aimed at counteracting the decline in production capacity and maintaining the reservoir condition.

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