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Updating conceptual model of Ciwidey-Patuha geothermal using dynamic numerical model

Updating conceptual model of Ciwidey-Patuha geothermal using dynamic numerical model

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Abstract. A study of Ciwidey-Patuha geothermal field using TOUGH2 reservoir simulation has been conducted. The purpose of this study is to verify and update previous Ciwidey-Patuha conceptual models. The numerical model of vapour-dominated reservoir with steam zone underlying liquid reservoir is constructed based on detail reservoir characterization from geoscience and well data. The reservoir boundary is defined based on TCH (temperature core hole) wells. The distribution of porosity, pressure, temperature and steam saturation are assessed. The model is validated by matching downhole data on pressure and temperature during exploration stage. Then for exploitation stage, the model is validated using reservoir pressure.

1. Introduction

Patuha geothermal field is located about 50 km southeast of the city of Bandung, West Java-Indonesia. Patuha field is a vapour-dominated with steam zone underlying deep liquid reservoir. The reservoir temperature about 215 – 230^{o}C covering area of 20 km^2. The steam zone about 700 meter thick is underlying on huge deep liquid water zone that makes this system unique to be built in numerical simulation. Ciwidey-Patuha geothermal field is managed by PT Geodipa Energi which has produced 60 MW to PLN since September 2014.

A series of numerical simulation in Patuha geothermal field have been carried out by West JEC in 2007 [1], ELC in 2013 [2], Schotanus in 2013 [3], Firdaus in 2016 [4], and Ashat & Pratama in 2017 [5] using TOUGH2 reservoir simulator which has been widely used to simulate geothermal reservoirs. All models consider Patuha as one big reservoir except Firdaus and Ashat which develop specific model for Ciwidey-Patuha [4, 5]. An updated version of Ciwidey-Patuha numerical model is based on Ashat and Pratama [5] by changing the bottom conditions of the model. The purpose of this study is to update the conceptual model.

2. Conceptual Model

The Patuha Geothermal System consists of three reservoirs associated with area of Kawah Putih, Kawah Ciwidey and Kawah Cibuni (Figure 1), according to the resistivity survey. It is also confirmed by thermal gradient measured at 150 m depth which shows three anomaly areas of high temperature [6] and ALOS PALSAR satellite imagery analysis [7] shows three lineament trending features which are probably identified as reservoir zone.

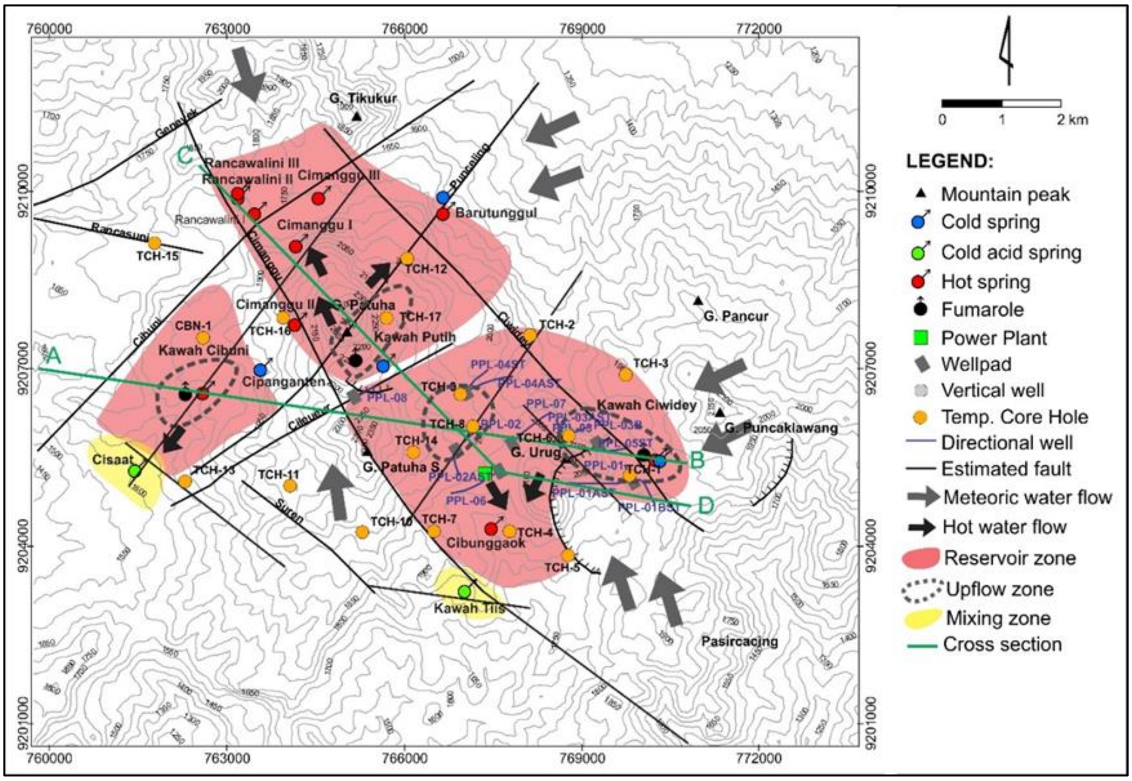

Figure 1. Lateral fluid flow pattern in Patuha Geothermal System (after [8]).

The surface manifestation in Kawah Putih such as fumarole and crater lake are indicated as an upflow zone of this system. The presence of fumaroles and boiling steam-heated waters in Kawah Cibuni and Kawah Ciwidey are expected to be the outflow of vapour dominated reservoir that allows the steam to reach the surface through the permeable zone.

The north-eastern part of G. S. Patuha or an area between wellpad 4 and wellpad 2 could be interpreted as the heat source location due to increased pressure and temperature within well PPL-02, liquid zone temperature of the well tends vertically static compared to others. It is also confirmed by chemical isotopes and gas characteristics [8], even though no surface feature represents the direct discharge of the deep reservoir around this area.

The magmatic vapour plume in Kawah Putih contributes to supply the deep steam reservoir of this system, that pressure and temperature within the steam reservoir increasing with respect to the magmatic plume [9]. It is probably separated from the vapour reservoir zone on the west and eastern part, due to geological structure controlled by Cimanggu Fault in the western and Cileueur Fault in the eastern part.

Ciwidey Fault and trending lineament of NE-SW and NW-SE around the Kawah Ciwidey region are expected as permeable pathways of production well in this area, correspond to the surface geological structure mapping [10] and gravity interpretation [8] as seen in Figure 1.

The deep reservoir of Patuha system is recharged by meteoric water in elevation 1.900 – 2.400 masl, which surrounds the centre of field, northwest, east and southwest part [11] as shown in Figure 2 and 3. It is associated with an area around the G. Tikukur, NE of G. Patuha, G. Puncaklawang, Pasircacing and southern part of G. S. Patuha. The peripheral meteoric water penetrates near G. S. Patuha and possibly quench the steam reservoir near this area [9]. Conceptual model of Patuha system is constructed by W-ESE cross section (A-B) as described in Figure 2 and NW-ESE cross section (C-D) as described in Figure 3. The cross section is reflected the reservoir characteristic of the area of Kawah Cibuni, Kawah Putih and Kawah Ciwidey (Figure 1) and reservoir of Kawah Putih and Kawah Ciwidey(Figure 2 and Figure 3).

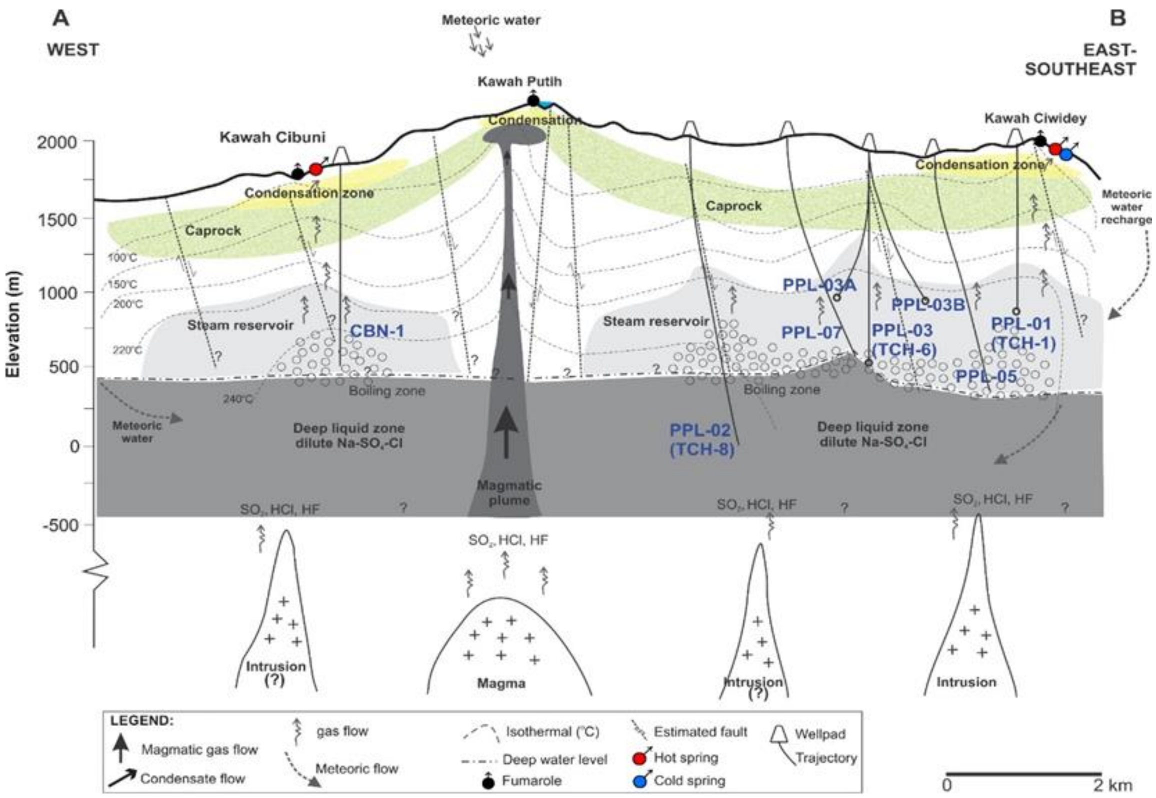

Figure 2. Conceptual model of Patuha Geothermal System in cross section C-D (after [8]).

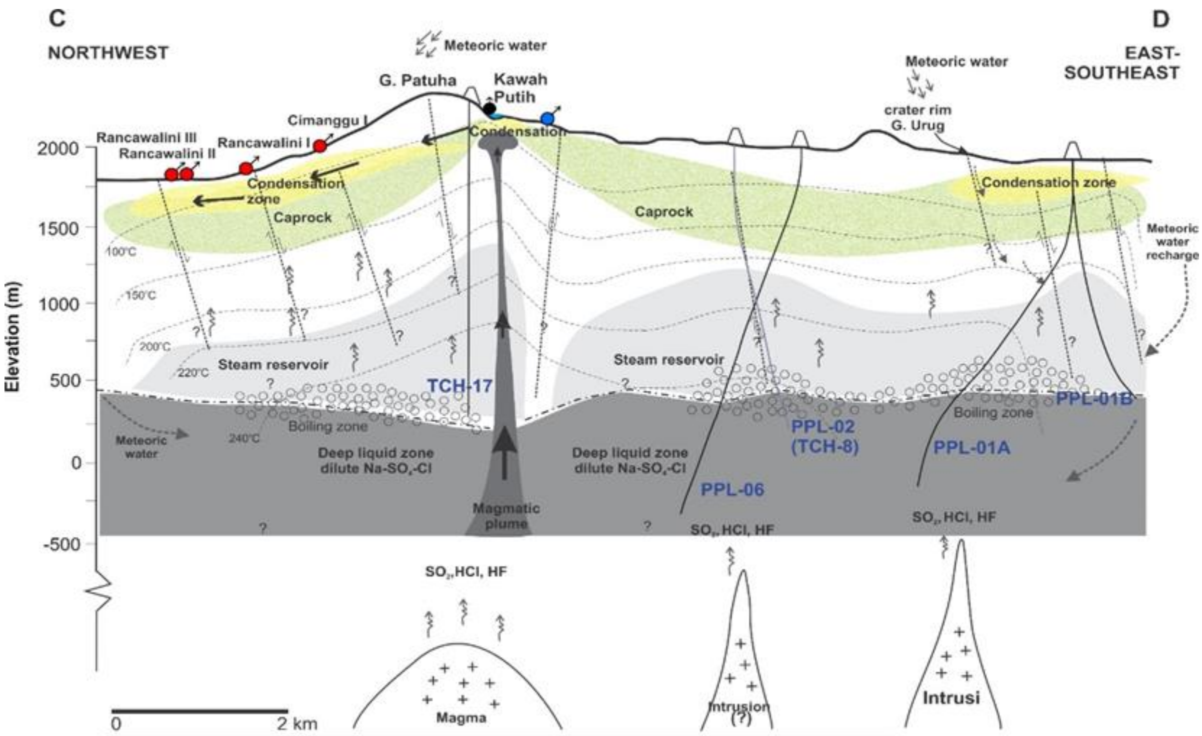

Figure 3. Conceptual model of Patuha Geothermal System in cross section A-B (after [8]).

Boiling condition within deep liquid reservoir leads the steam separated and rises to vapour-dominated zone in the Patuha system. Steam condensation occurs and percolates downward the deep liquid zone, which may have formed dilute and neutral Na-SO_4-Cl waters. A steam reservoir in Kawah Ciwidey zone flows vertically toward the area of G. Urug following Ciwidey Fault, and discharge fumarole in eastern part of Kawah Ciwidey. Hot spring also present in this area, whose sulphate acid water type, as steam-heated water due to groundwater heated by steam of the reservoir near shallow depth (Figure 2 and Figure 2). The produced steam in eastern part of PPL-01, PPL-05, PPL-03 and PPL-07 are supplied by the reservoir which is associated with G. Urug. While the PPL-02 in the western part is associated with the potential heat source of the western part (Figure 2). Corresponding to chemical analysis of production wells i.e. PPL-01, PPL-01B, PPL-03, PPL-03A, and PPL-03B, those wells have the same characteristics of gas composition, but different with PPL-02 and PPL-02A. It suggests that different heating systems affect eastern and western area.

Well PPL-06 is presumably supplied by the same source as PPL-02 and location of both wells is close each other (Figure 3). On the other hand, PPL-01A is a deepest well drilled in wellpad 1 and is non-productive well. Based on chemical analysis, steam condensation occurs within this well due to meteoric recharge infiltrated through the crater rim of G. Urug, as the trajectory direction of PPL-01A close to this location (Amelia, 2014). Whereas, PPL-01B is situated in the east corner, is dedicated as an condensate injection well at elevation of 500 – 700 masl. Recharge of meteoric water is expected around G. Puncaklawang and Pasircacing [10].

Well CBN-1 is a well drilled in 1996 reached elevation of 455 masl penetrates the vapour zone at elevation of about 1,000 masl with a maximum temperature of 240^{o}C. Steam from Kawah Cibuni reservoir zone flows toward surface through NW-SW trending fault which controls the appearance of fumarole sulphate-acid spring in this location (Figure 3).

Fluid of Kawah Putih crater lake is mainly related to magmatic gases derived from magmatic vapour plume which rises toward surface at the centre of Kawah Putih. As steam condenses and enters shallow aquifer or surface water, it affects water of the lake. Meanwhile, the occurrence of fumarole in the lake shore is a direct discharge of steam reservoir. Based on chemical composition, no magmatic gases found in the discharging steam. The existence of the Kawah Putih reservoir zone is indicated by the TCH-17 well that penetrates the vapour zone at elevation of about 1,400 masl with a maximum temperature of 240^{o}C. Magmatic steam condensate in Kawah Putih flows laterally to the NW slopes of G. Patuha and probably mixes with steam condensate from vapour dominated reservoir

3. Computer Model

3.1. Gridding and Layering

Ciwidey-Patuha numerical model is built in TOUGH2. Even though non-condensable gas content exists in the steam, the EOS1 model (for water and water with a tracer) is chosen to simplify the modelling process without ignoring the important parameters. The computer model covers an area of 5.5 km x 5.5 km with total depth of 3 km. The maximum elevation of surface model is 2010 masl and the lowest is – 1000 masl. The model consists of 15 layers. The structure direction trend is based on the major geothermal conduit, the Ciwidey Fault, which is about 47^{o} from north to west to accommodate the predominant heat and fluid flow directions.

The model is constructed by single porosity model with the rectangular grid. The model is divided into 5 type of major layers i.e. atmosphere, groundwater, vapour, liquid, and basement. The surface/atmosphere has a thickness of 10 m, the groundwater and vapour thickness is 800 m each divided into 4 cells, the liquid thickness is 1000 m divided into 5 cells, and basement thickness is 400 m. The total number of blocks is 7260 blocks.

3.2. Internal and Boundary Conditions

The atmospheric condition is set as the top boundary. It is assigned to a constant pressure of 1 bar and a constant temperature of 25°C. This layer uses huge volume factor to keep the properties constant, therefore, the top layer is not influenced by reservoir conditions over time.

The side boundary is assumed to be no-flow boundary and the materials are treated to be impermeable especially the side boundary of vapour dominated zone. The range of permeabilities is 0.1 to 0.01 mD. Figure 4 shows the side boundary of Ciwidey-Patuha computer model covering the reservoir.

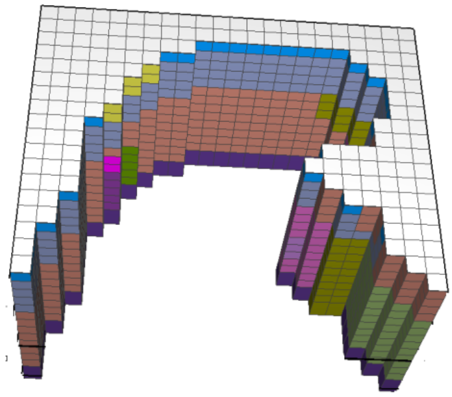

Figure 4. Side boundary of Ciwidey-Patuha model.

Bottom boundaries are basement layer and heat sources. The basement layer is treated as an impermeable layer while the heat source is set to the fixed state with temperature of 300°C and pressure of 130 bar located below PPL-2. The other heat source, as intrusion located below G. Urug, PPL-3 Pad, is set with temperature of 300°C and pressure of 110 bar as a fixed state. The location of the heat sources in this model shown in red blocks in Figure 5.

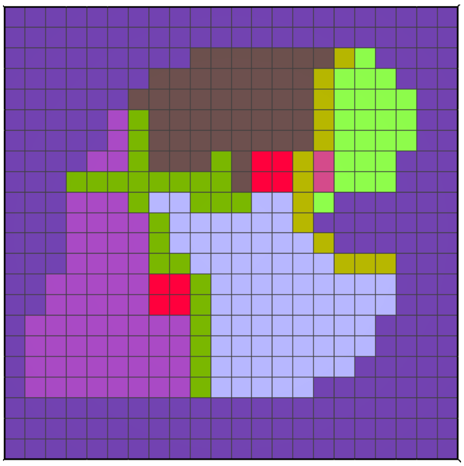

Figure 5. Bottom boundary.

3.3. Material Properties

The rock parameters are assigned to define a certain type of material properties such as specific heat, wet heat conductivity, rock density, porosity, and permeability (x, y, z direction) in the TOUGH2 V.2.0 [12]. The most important property in natural state calibration is permeability and porosity. The permeability will affect the pressure and temperature distribution as well as heat and fluid flow direction in the model. The anisotropy of permeability rock was considered only for the ratio between vertical and horizontal permeability. Then the lower value of vertical direction, $k_z < k_{xy}$ has been assigned. The rock characteristics curve, relative permeability, uses Corey's Curve and has been assigned to all material rock data. This parameter has an impact on the mobility of liquid phase within the vapour-dominated reservoir under steady state conditions and during reservoir exploitation. Based on field data, there are no indications of double porosity behavior. **Table 1.** shows all the calibrated permeability and porosity data that represent the rock properties. The 3D model of final rock properties distribution in the Ciwidey-Patuha model is shown in Figure 6 based on the interpretation of conceptual model.

Table 1. Material properties.

Material	Porosity	k_{xy} (m^2)	k_z (m^2)
RESV1	0.10	1.00E-13	5.00E-14
RESV2	0.10	8.00E-14	4.00E-14
RESV3	0.10	8.00E-14	4.00E-14
RESL1	0.10	5.00E-14	2.00E-14
RESL2	0.07	4.00E-14	2.00E-14
RESL3	0.05	2.00E-14	1.00E-14
RSVG	0.08	2.00E-15	1.00E-15
FCIWI	0.15	3.00E-14	3.00E-14
FBDTL	0.125	2.50E-14	2.50E-14
FCIMA	0.125	2.00E-14	2.00E-14
FBLTG	0.10	3.00E-15	3.00E-15
SEAL1	0.05	8.00E-15	8.00E-15
UPZ05	0.10	8.00E-14	4.00E-14
UPZ02	0.10	8.00E-13	4.00E-13
SEAL2	0.05	1.00E-17	1.00E-17

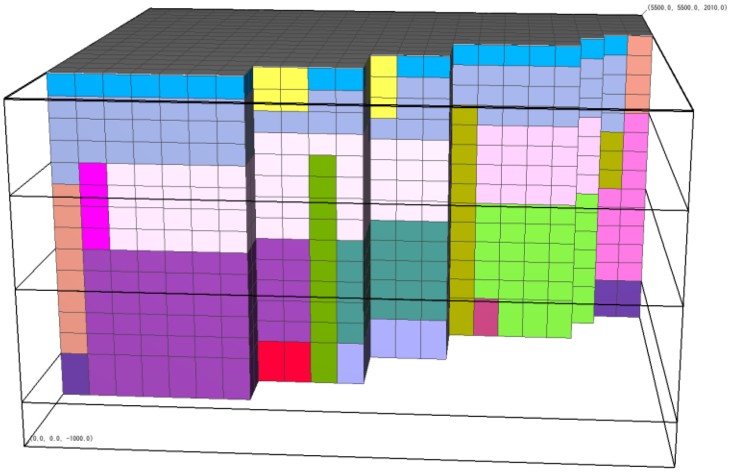

Figure 6. Rock properties distribution.

4. Natural State

The first step in model calibration is to perform initialization or commonly called as natural state model. The objective of the natural state model is to reproduce the initial condition both pressure, temperature and fluid saturation distributions. The properties of the reservoir model is constructed from material data and with their specific properties. The model is then run until steady state is achieved. This is reached when the time is considered infinite (>10^{15} seconds). Pressures and temperatures are best presented as well-by-well matches between observed data and model results. In addition, the mass and the heat flow profile of the conceptual model was used as a calibration for the output model reservoir. The numerical

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simulation of the Ciwidey-Patuha geothermal field, with respect to both the fluids natural state, is based essentially on the conceptual model of the field itself and on the analysis of the characteristics of the wells from the thermodynamics.

4.1. Pressure and Temperature Matching

The pressure and temperature of the model are validated using 10 TCH wells (the core hole well) and 14 PPL wells (production or injection well). Figure 7 and Figure 8 show the matching results for PPL wells and TCH wells respectively. The PPL wells are located in the production area while the TCH is a temperature gradient hole which mostly drilled maximum to the cap rock. It shows a good match between model and downhole data.

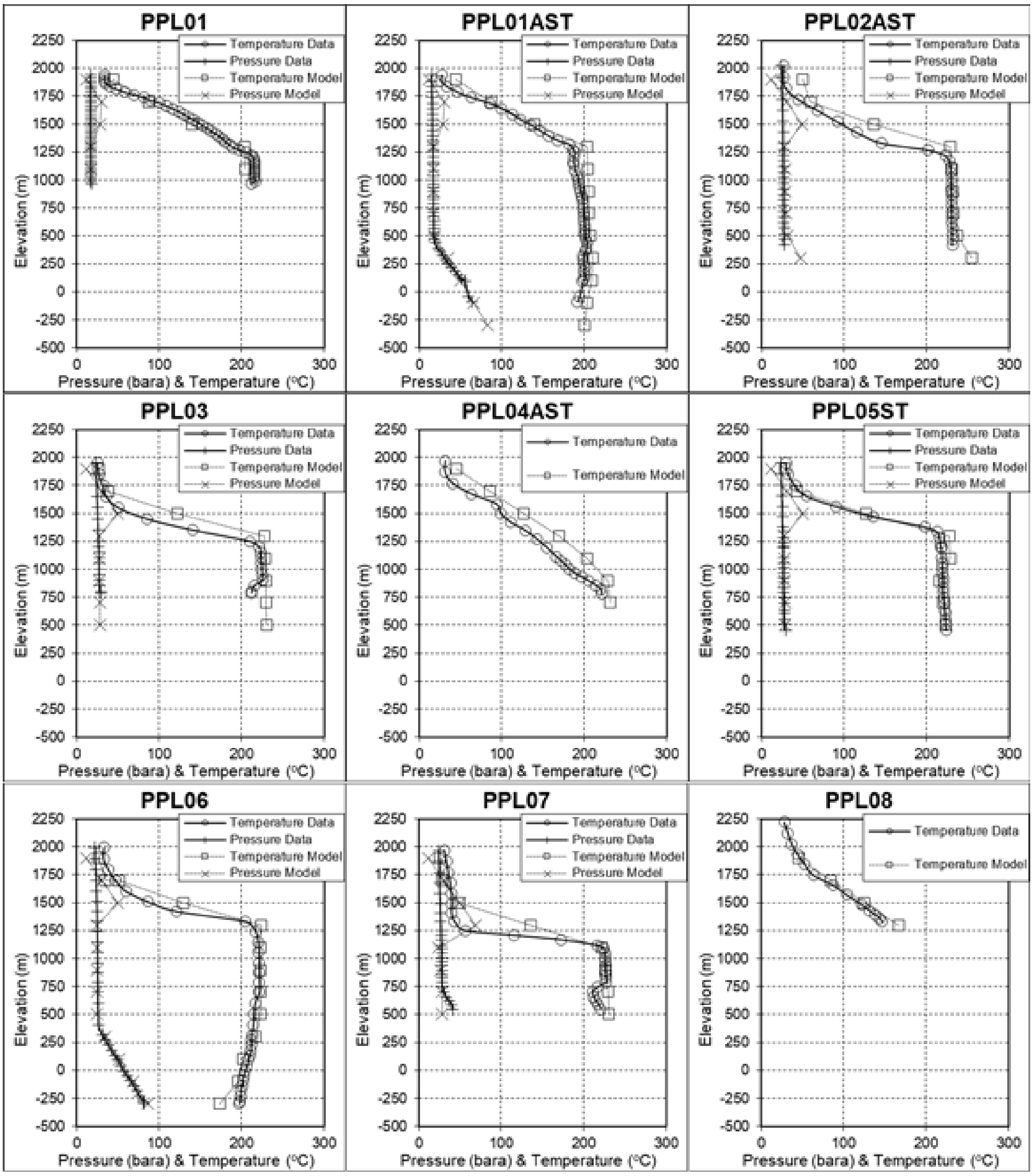

Figure 7. The comparison of observed and simulation results - pressure &temperature matching of PPL wells.

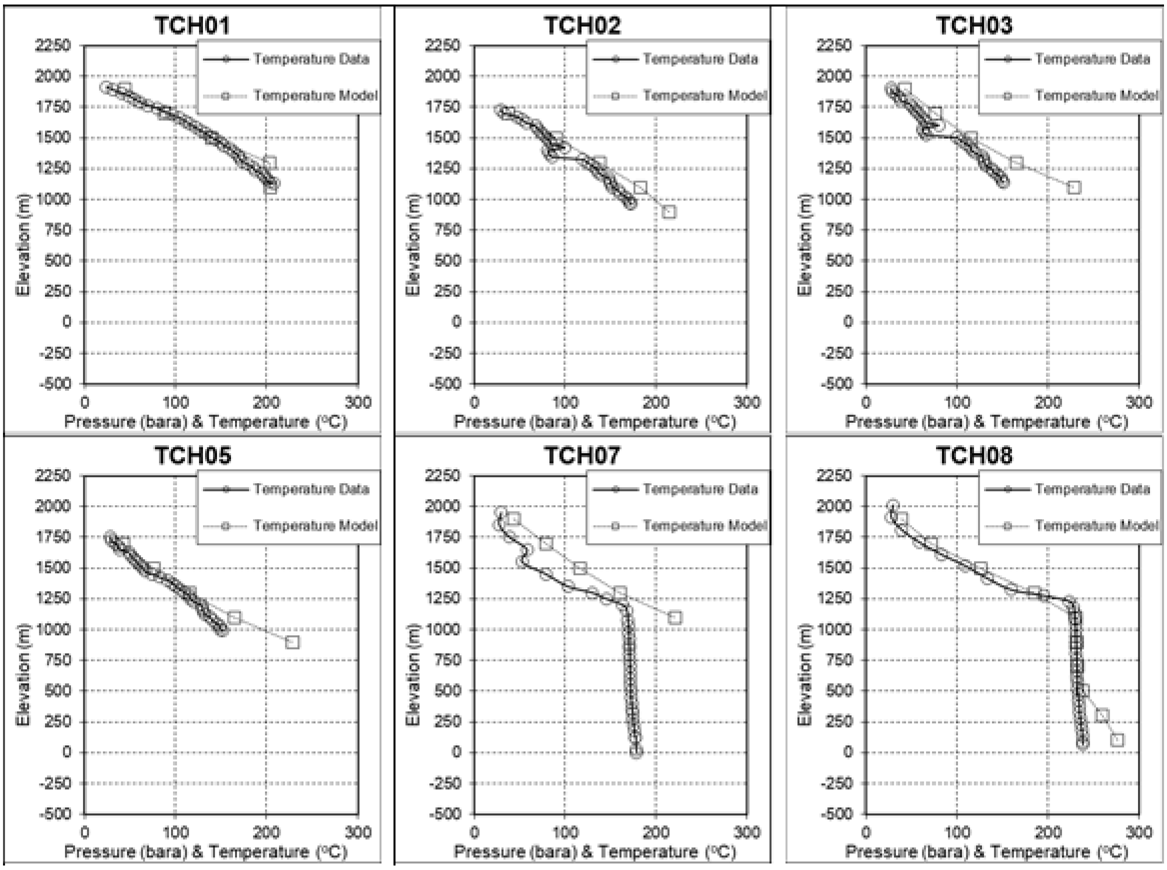

Figure 8. The comparison of observed and simulation results - temperature matching of TCH wells.

The pressure and temperature in the shallow reservoir show a static pressure and convective temperature indicate the saturated steam and high permeability reservoir (PPL-2AST, PPL-03AST, PPL-05ST, PPL-07). Otherwise, the deep reservoir shows a liquid phase (PPL-01AST, PPL-06) because at the elevation below 500 masl it has a hydrostatic pressure profile which indicate a compressed liquid. The presence of liquid column [13] has also been proved by the pressure gradient change of model at about 500 masl accompanied by below saturation temperature profile. The pressure gradient change is caused by the change in density of water in which the liquid condition has greater density, so does its hydrostatic pressure. All the PPL wells show convective temperature profiles indicating production area has a good permeability. Based on the characteristics of well data, the Ciwidey-Patuha geothermal field is vapour-dominated with steam zone underlying deep liquid reservoir.

TCH (temperature core holes) were drilled to know whether there is temperature gradient anomalies. Interpretation of TCH data helps delineate the reservoir boundary. Conductive thermal gradient implies outside reservoir location with low permeability.

4.2. Heat and Mass Flow

The 3D temperature, pressure and gas saturation profile of Ciwidey-Patuha shown in Figure 1. Based on Ciwidey-Patuha natural state model, the temperature of the reservoir is 230°C and the pressure is 27 bars. The steam zone thickness is about 800 – 1000 m.

The temperature distribution on the vertical sector shows the convection in the reservoir (Figure 9). Therefore, it controls the thermal anomaly within the Ciwidey-Patuha reservoir. The pressure distribution in the same sector suggests the reservoir pressure is likely a hydrostatic pressure. The temperature in the reservoir is mainly controlled by the steam upflow zones and the convective flow within the vapour-dominated reservoir. The heat recharge is present at the base of the liquid reservoir. The conductive heat transfer occurs from the heat source within the basement into the reservoir, while the convective heat transfer occurs in the entire steam zone.

The gas phase expands laterally, flowing from west to southeast direction (Figure 9). The steam upflows produce a higher gas saturation in the central part of the steam reservoir area. This model has the gas saturation in a range of 30% to 65%. As a comparison with similar vapour-dominated reservoir models in Pratama and Saptadji [14] which has a maximum 80% gas saturation while Grant & Bixley [15] suggests the value of 85%. The transition zone between steam and liquid reservoir occurs at 200 – 0 msal where the boiling occurs.

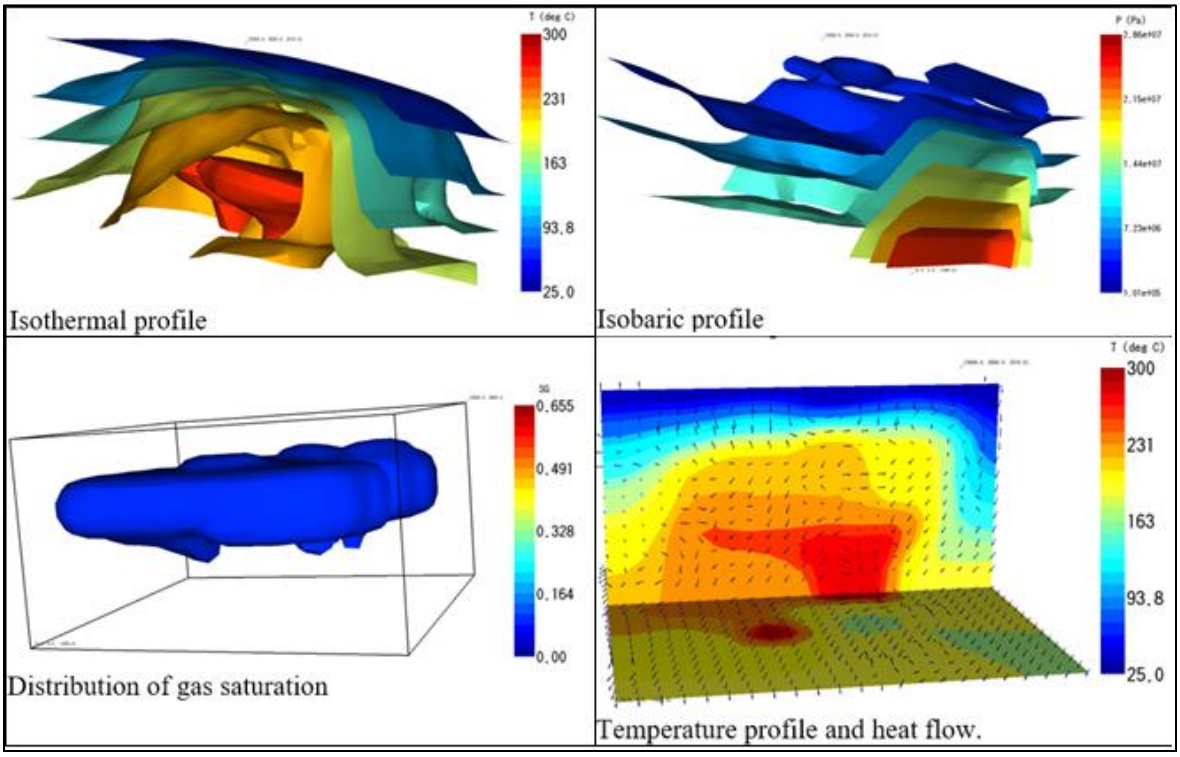

Figure 9. 3D profile of pressure, temperature and gas saturation profile.

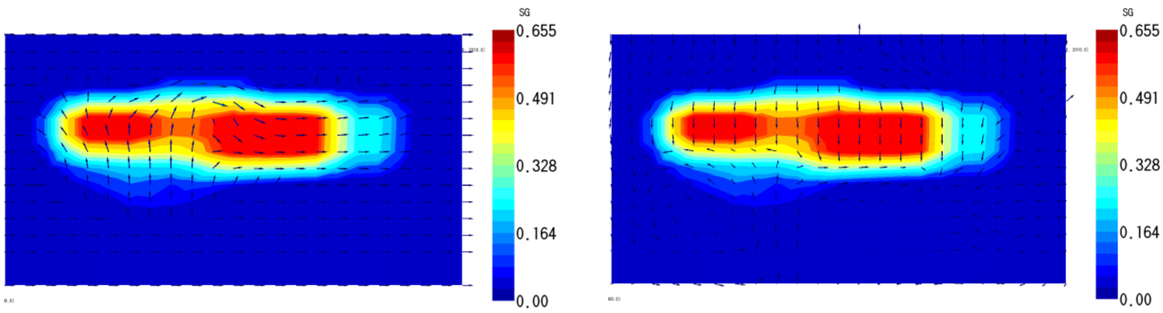

Figure 10. Gas saturation profile on steam flow (left) and liquid flow (right).

The heat loss by conduction through the cap rock and the lateral impermeable layer boundary restricting the vapour-dominated reservoir. As a consequence of a heat loss, a fraction of steam condenses and generating a downward flux of a condensate. The downward movement of the steam condensate (Figure 10), is resulted by the effect of the condensate as the density of condensate is naturally higher than the steam. Those processes are suitable with D'Amore and Truesdell model [13]. The concept of fluid movement within the Ciwidey-Patuha reservoir is counterflow heat transfer. This occurs continuously hence the pressure gradient shows uniform steam pressure (34 bar) and temperature 245°C throughout the whole steam cap [15].

5. History Matching

The natural state of Ciwidey-Patuha model then used for production runs to simulate the changes under exploitation. Based on production history data of Ciwidey-Patuha that generated 60 MW for single unit, the calibration of history matching can be conducted.

Figure 11 shows a matching pressure in PPL-01, PPL-02, PPL-03, PPL-05 between pressure output from the model and well pressure. Due to wells in Ciwidey-Patuha produces steam, it is necessary to have an accurate feed zone depths.

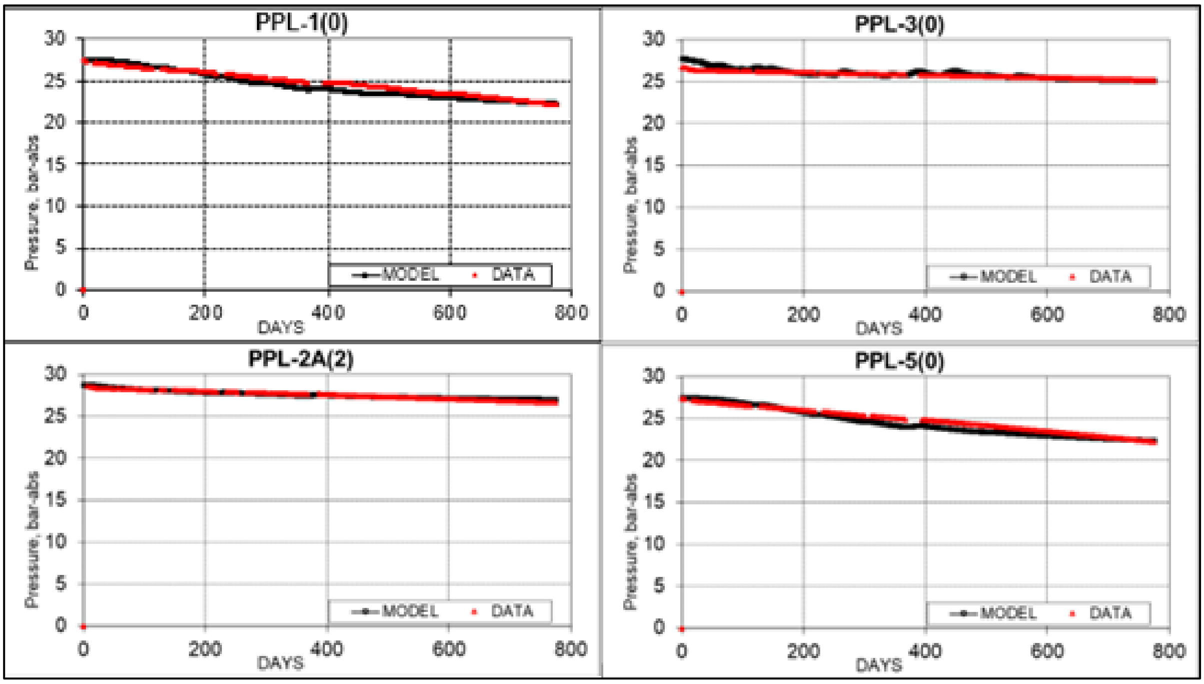

Figure 11. History matching of reservoir pressure

6. Conclusion

- The numerical simulation of Ciwidey-Patuha geothermal field has been successfully developed and resulted a good match both in natural state condition and production history.
- The model is able to verify and update the conceptual model of the field.
- The heat sources are located below PPL-02 Pad and G. Urug.
- The Ciwidey-Patuha is a vapour-dominated reservoir with deep liquid reservoir underneath the steam zone.
- The vapour dominated reservoir has 230°C temperature and 27 bar pressure.

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