Application of experimental design in geothermal resources assessment of Ciwidey-Patuha, West Java, Indonesia

Ali Ashat¹, Heru Berian Pratama¹
¹Geothermal Engineering Study Program, Institut Teknologi Bandung, Indonesia
Jl. Ganesha No.10, Bandung, West Java, Indonesia. 40132
heru.berian@geothermal.itb.ac.id

Abstract. The successful Ciwidey-Patuha geothermal field size assessment required integration data analysis of all aspects to determined optimum capacity to be installed. Resources assessment involve significant uncertainty of subsurface information and multiple development scenarios from these field. Therefore, this paper applied the application of experimental design approach to the geothermal numerical simulation of Ciwidey-Patuha to generate probabilistic resource assessment result. This process assesses the impact of evaluated parameters affecting resources and interacting between these parameters. This methodology have been successfully estimated the maximum resources with polynomial function covering the entire range of possible values of important reservoir parameters.

1. Introduction
Patuha geothermal field is located in west Java, Indonesia, about 50 km southwest of the city of Bandung. Patuha field is one of vapor-dominated geothermal system in Indonesia with liquid deep zone included and temperature about 210 – 230°C covering 20 km2. The steam cap about 700 m is underlying on huge deep liquid water zone that makes this system unique to be built in numerical simulation. Recently, Patuha field is operated by PT. Geodipa Energi which has produced 55 MWe to PLN in 2015.

The uncertainties in both subsurface parameters and the development to implement in Ciwidey geothermal field resources can be accommodate used probabilistic assessment. The geothermal developer has done this through using heat stored method with Monte Carlo simulation. The range of parameter values in these method covers the range of uncertainty for that particular variable. The proposed method for this study is experimental design with reservoir numerical simulation. Experimental design is a schematic was of simultaneously testing multiple variable that effect a response. A full factorial was used in this study. The objective of this study are build numerical simulation of Ciwidey geothermal field based probabilistic resource assessment.

2. Methodology
Experimental design (ED) is the process of planning a study to meet specified objectives. ED was used to reservoir simulation with probabilistic approach in order to study the reservoir model from uncertainty parameters. Therefore the field capacity as the amount of electricity generation (MW) from heat and mass production can be determined.

These study used a full factorial of 3 factor. The relationship of 2 level between all the 3 parameter may be estimated by a response polynomial or proxy equation (Equation 1).
\[ Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 AB + \beta_5 AC + \beta_6 BC + \beta_7 ABC \]  

(1)

Where \( \beta_0 \) is the average value of the response and \( \beta_1, \beta_2, \ldots, \beta_7 \) is regression linear. The polynomial describes the behavior of the responds between parameter including the interaction effects between parameters.

The parameters that have high uncertainty are liquid saturation (SL), porosity (\( \phi \)), and permeability (\( k_{xyz} \)). These are the reference model parameters and it chosen for ED parameters.

The methodology shown in Figure 1. The conceptual model gives the general description to develop numerical model using TOUGH2 with interface. While the ED and polynomial equation generated from commercial experimental design.

3. Conceptual Model
Patuha Geothermal System is consist of three reservoirs, there are associated with area of G. Patuha, G. S. Patuha, and extend toward W-NW part and G. Urug (Figure 2), according to the resistivity survey. It is also confirmed by thermal gradient measurement at 150 m depth shows three anomaly area of high temperature [1] and ALOS PALSAR satellite imagery analysis [2] shows three lineament trending feature are probably identified as reservoir zone. The surface manifestation in Kawah Putih such as fumarole and crater lake is indicated as upflow zone of this system. The presence of fumaroles and boiling steam-heated waters in Kawah Cibuni and Kawah Ciwidey would be expected to upflow of vapor dominated reservoir, that allow the steam to rise toward the surface through permeable zone. The northeastern part of G. S. Patuha or definitely in area between wellpad 4 and wellpad 2 is probably interpreted as upflow zone due to increased pressure and temperature within well of PPL-02, liquid zone temperature of well is statically compared to others and also confirmed by chemical isotope and gas characteristic [3]. Eventhough, no surface feature as consequent the direct discharge of deep reservoir around this area.

The magmatic vapor plume in Kawah Putih contributed to supply the deep steam reservoir of this system [4] that pressure and temperature within steam reservoir increasing respect to magmatic plume. It is probably separate with the vapor 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 (figure 2). Ciwidey Fault and trending lineament of NE-SW and NW-SE around Kawah Ciwidey region are expected as permeable pathways of production well in this area, correspond to the surface geological structure mapping [5] and gravity interpretation from West JEC [3] as seen in figure 2.
Figure 2. Lateral fluid flow pattern in Patuha Geothermal System [5].

Figure 3. Conceptual model of Patuha Geothermal System in cross section A-B.
The deep reservoir of Patuha system is recharged by meteoric water in elevation 1.900 – 2.400 m asl, which is surround the centre of field, northwest, eastern and southwest part [6] as shown in figure 2. It is associated with area around G. Tikukur, NE of G. Patuha, G. Puncaklawang, Pasircacing and southern part of G. S. Patuha. Layan (2003) also reported that periperal meteoric water penetrate near G. S. Patuha and possibly quench the steam reservoir near this area.

Conceptual model of Patuha system is constructed by W-ESE cross section (A-B) as describe in figure 2. The cross section is reflected the reservoir characteristic of area of Kawah Cibuni, Kawah Putih and Kawah Ciwidey (figure 3).

Boiling condition within deep liquid reservoir lead the steam separated and give rise to vapor-dominated zone in the Patuha system. Steam condensation occurs and percolates downward the deep liquid zone, which may formed dilute and neutral Na-SO4-C1 waters. Steam reservoir in Kawah Ciwidey zone flows vertically toward area of G. Urug following Ciwidey Fault, and discharge fumarole in eastern part of Kawah Ciwidey. Hot spring also present in this area, whose sulfate acid water type, as steam-heating water due to groundwater heated by steam of reservoir near shallow depth (figure 3). The steam of production well in eastern such as PPL-01, PPL-05, PPL-03 and PPL-07 are supplied by reservoir which is associated with G. Urug. While the well of PPL-02 in the western part is connected with potential heat source in western part (figure 3). Corresponding to chemical analysis of production well, some of well such as PPL-01, PPL-01B, PPL-03, PPL-03A, and PPL-03B has same characteristic of gases composition, but different with PPL-02 and PPL-02A. It suggests that a different heating system is affected it.

Well of PPL-06 is presumed that supplied by the same source as PPL-02. On other hand, PPL-01A is a deepest well drilled in pad 1 and is not produced now. Based on chemical analysis, steam condensation occurs within this well due to meteoric recharge infiltrated through crater rim of G. Urug, as the trajectory direction of PPL-01A closed to this location [3]. Whereas, PPL-01B is situated in east corner, is purposed as injection well of PT. Geo Dipa. Reversal temperature occurs within this well due to groundwater influx in depth at elevation of 500 – 700 m asl. It is expected to recharge of meteoric water around G. Puncaklawang and Pasircacing [3].

Fluid of Kawah Putih crater lake is mainly related to magmatic gases derived from magmatic vapor plume that rising toward surface at the central of Kawah Putih, as condensation of steam into shallow aquifer or surface water affect the lake water. Meanwhile, the occurrence of fumarole in the shore of lake direct discharge of steam reservoir, based on chemical composition, no magmatic gases contained in it. The existence of the Kawah Putih reservoir zone is indicated by the TCH-17 drilling wells that penetrates the vapor zone at elevation of about 1,400 m with a maximum temperature of 240°C. Magmatic steam condensates in Kawah Putih flows lateral to the NW slopes of G. Patuha and probably mixture with steam condensate from vapor dominated reservoir.

4. Ciwidey Numerical Model
A numerical model is constructed with conceptual model. Therefore it is set of interconnected elements which each of them represents of actual subsurface. The thermal and rock properties of the rock materials are represented as the thermodynamic properties of fluids of reservoir. To confirm that the constructed numerical model represents the Ciwidey-Patuha reservoir, it is subjected to two steps of calibration. The first is a natural state and the second step is a history matching calibration. In this study, after natural state is attained therefore the model run for experimental design (table 1). Material data for computer model.

The numerical model in these study is limited to ciwedey reservoir because GeoDipa generated 55 MW production from steam cap. The numerical model rotated parallel with Ciwidey fault as a main fault (Figure 4). Ciwidey grid/block of numerical model). The computer model has grid size of 5.5 x 5.5 km with rectangular mesh (250 x 250 m). The model is divided into 15 layers corresponding to 3.01 km in total thickness (2,010 msal to -1,000 msal). The layers have different thickness depending on the region (Figure 5). The atmosphere, reservoir and bottom layer are 10 m, 200 m and 500 m respectively. The total block from Ciwidey computer model is 7,260 blocks. The top layer as atmosphere was set
homogenously at 1 bar and 25°C for initial pressure and temperature respectively. Bottom layer, heat source, was set 120 bar and 317°C it is based on the conceptual model with inflow around Mt. Patuha and Mt. Uruq. The side boundary using hydrostatic pressure and normal temperature gradient to represent the surrounding environment condition. At side boundary of the model is in impermeable condition which is there are no flows of both heat and mass during natural state condition.

Table 1. Material Data.

| Material | Porosity | kxy (m²) | kz (m²) |
|----------|----------|----------|---------|
| 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|
| UPZ07    | 0.10     | 8.00E-14 | 4.00E-14|
| UPZ02    | 0.10     | 8.00E-13 | 4.00E-13|
| VERTI    | 0.10     | 8.00E-13 | 4.00E-13|
| SEAL2    | 0.05     | 1.00E-17 | 1.00E-17|

Figure 4. Ciwidey grid/block of numerical model.

The numerical model should represent actual conditions based on the information from conceptual model. Thus the material properties that represent rock type for the model should be assign into the computer model. It consist of density, porosity, permeability, thermal conductivity and specific heat. Additionally the relative permeability corey and relative liquid saturation 0.3 applied in these model (Permeability and porosity are considered as most important parameter in order to have steam cap underlying brine reservoir natural state model (Table 1).
5. Ciwidey Natural State
The main objective of the natural state calibration is to verify the pressure and temperature distribution and the heat and mass flow of the model. Pressure and temperature profile at natural state shown at Apendix A. It shows a good match of pressure and temperature between a model output and actual well data for PPL and TCH Wells. The simulated pressure and temperature profiles at existing production wells, PPL-02 and PPL-06 for example (Figure 6. Matching on the pressure and temperature profile of PPL-02 and PPL-06 Well.), has reproduced the steam dominated at top of the reservoir underlying liquid dominated reservoir. While the TCH well shown a conductive heat transfer because it through impermeable layer.

Figure 5. Ciwidey numerical block at steam cap layer.

Figure 6. Matching on the pressure and temperature profile of PPL-02 and PPL-06 Well.
Figure 7. The temperature cross-section of natural state Ciwidey Model.

Figure 8. The gas saturation cross-section of natural state Ciwidey Model.

Figure 9. The heat transfer at natural state Ciwidey Model.

The cross-section of natural state model shown at Figure 7 and Figure 8 for temperature and gas saturation. These has similarity with Ciwidey conceptual model shown in Figure 3. The heat source in these model is Kawah Putih as main heat source and intrusion at the bottom of Urug Mountain. Hot
water is heated by a hot reservoir rock and will go up through good vertical permeability because high temperature fluids has a lower density. The boiling zone will segregate vapor phase and liquid phase then the steam cap will form and will be moved laterally the reservoir and spread (Figure 9). The gas saturation on the steam cap has a maximum value around 65%. The PPL-02 well is affected by a heat source indicated by higher temperature. PPL-06 indicated has a main heat source as PPL-02.

6. Sustainability
The experimental design (ED) concept were applied in Ciwidey reservoir model in order to study the dependency from uncertain reservoir parameters of to know the amount of production (MW) for 30 years. It also has a purpose to derive a proxy model (polynomial equation) to the reservoir simulation in the probabilistic Monte Carlo simulation.

There are 3 main parameters were investigated: liquid saturation (SL), matrix porosity (ϕ), and permeability (k_{xyz}). The low and high value from matrix porosity and permeability are ±20% deviations from material properties as shown in Table 2.

| Parameter                  | Low (-1) | High (+1) |
|----------------------------|----------|-----------|
| Liquid saturation (SL)     | 0.3      | 0.5       |
| Matrix Porosity (ϕ)        | -20% from base | +20% from base |
| Permeability (k_{xyz})     | -20% from base | +20% from base |

A two level (low and high) of full factorial with three factor for ED was implemented. The total run in these study is 8 runs for 30 years of production. In the design table (Table 3), the standard order column is an experimental design idea to do the experiments in a random order (run order) and avoid run-dependent effects.

| StdOrder | RunOrder | SL | ϕ          | k_{xyz} |
|----------|----------|----|------------|---------|
| 7        | 1        | -1 | 1          | 1       |
| 2        | 2        | 1  | -1         | -1      |
| 4        | 3        | 1  | 1          | -1      |
| 1        | 4        | -1 | -1         | -1      |
| 5        | 5        | -1 | -1         | 1       |
| 3        | 6        | -1 | 1          | 1       |
| 6        | 7        | 1  | -1         | 1       |
| 8        | 8        | 1  | 1          | 1       |

The reservoir simulation were run equally distributing using well on deliverability method with PI 2.0E-12 m^3 and WHP 10 bar. The total production into 37 wells with targeting at steam dominated reservoir. The power capacity (MW) estimated by steam production over time project times specific steam consumption shown in Equation 2.

\[
MW_e = \frac{\sum_{t=1}^{L} m \times \Delta t}{L \times SSC}
\]

Where MW_e is the power capacity, m is steam produced (kg/s), \( \Delta t \) is delta time at simulator (years), L is time project (years) and SSC is specific steam consumption (kg/s/MW).

The results of Ciwidey ED for 30 years of steam production with 2.016 kg/s/MW of SSC shown in Table 4. The minimum power capacity is 124.5 MW and the maximum is 131.1 MW.

The Ciwidey numerical simulation are approximated by polynomial equation to generate the power capacity (MW_e). The polynomial equation of power capacity as a function of three independent
parameters are the results in these study. A two level proxy model using -1 and +1 parameters to generate the power capacity responses for a Ciwidey model shown in these Equation 3.

Table 4. The results of Ciwidey ED.

| RunOrder | MWe   |
|----------|-------|
| 1        | 128.4 |
| 2        | 126.5 |
| 3        | 126.3 |
| 4        | 125.3 |
| 5        | 129.9 |
| 6        | 124.5 |
| 7        | 131.1 |
| 8        | 130.4 |

\[
MWe = 127.8 + 0.7670*SL - 0.4074*\phi + 2.132*k + 0.1789*SL*\phi + 0.02135*SL*\phi - 0.1459*\phi*k + 0.01660*SL*\phi*k
\]

The next step are running Monte Carlo simulation based on generated polynomial equation of power capacity with 50,000 iterations using spreadsheet. The result is a probability distribution function of the power capacity covering the full range of possible outcomes. The cumulative distribution for 30 years steam production of the power capacity shown in Figure 10. The P10, P50 and P90 are 126 MW, 128 MW and 129 MW respectively.

![Figure 10. Monte Carlo simulation results with histogram and cumulative distribution function with P10, P50 and P90 indicated.](image)
7. Conclusion

1. The model of Ciwidey-Patuha geothermal field with 5.5 km x 5.5 km area has successfully developed and it showed a good match with actual PPL well and conceptual model.
2. The numerical simulation with Experimental design has successfully applied for Ciwidey-Patuha geothermal field.
3. The probabilistic power capacity using Monte Carlo based on experimental design for 30 years production, P10-P50-P90, are 126 MW, 128 MW and 129 MW respectively.

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