Reservoir Modeling of Sorik Marapi Geothermal Field

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Keywords: Sorik Marapi, Indonesia, Well testing, Natural State, Conceptual Model

ABSTRACT

Sorik Marapi Geothermal Field is located west and northwest of Sorik Marapi, an active andesitic stratovolcano, on the western splay of the Sumatra Fault Zone (SFZ) and within the Panyabungan Graben. A conceptual model of the reservoir has been developed by integrating the geology, geophysics, geochemistry and well testing results obtained to date. The conceptual model is characterized by a primary upflow originating in the fractured basement rocks located slightly northwest of pad A in the drilled area with a temperature of >280°C. The conceptual model was used to develop a 3-D numerical natural state model; the model was calibrated by matching feedzone pressures and temperature profiles in wells. The calibrated natural state model was in turn employed to make a preliminary assessment of the production capacity of the drilled area. As geothermal development brings additional data from geoscientific studies, drilling and testing, the conceptual and numerical reservoir models will be updated.

1. INTRODUCTION

Sorik Marapi Geothermal Power Ltd. (SMGP) is developing the Sorik Marapi Geothermal Field located west and northwest of Sorik Marapi, an active andesitic stratovolcano, on the western splay of the Sumatra Fault Zone (SFZ) and within the Panyabungan Graben. The license area covers an area of about 629 km²; the initial development is focused on the area east of the stratovolcano (Figure 1). To-date, more than 15 wells have been drilled and tested. The Sorik Marapi area is underlain by a generalized lithologic sequence of three formations. The Sibanggor Volcanics, composed of dacitic to andesitic breccias and tuffs, overlie the sedimentary basement. The Roburan Volcanics, comprised of dacite, tuff, and altered volcaniclastic units, lie in between the Sibanggor and Sorik Andesite related to recent volcanism.

At the time (2017) the work described in this paper was performed, data from C-, D- and P-pad wells shown in Figure 1 were not available. A conceptual model of the geothermal reservoir near Pad A was developed by integrating available (as of 2017) geological, geophysical, geochemical, and well test data. According to the conceptual model, the primary hot water upflow with a temperature greater than 280 °C originates in the fractured basement rocks located to the west of A-pad (Figure 2). The reservoir in the vicinity of Pad A is developed in distributed fracture permeability within the Sibanggor Formation and in the lower portion of the overlying young volcanics, but significantly controlled by permeable faults oriented with the current stress field to be propped open. The convecting near-neutral chloride reservoir outflows primarily to the SE in a relatively thin outflow tongue (perhaps ~100 to 200 m thick) at an elevation of approximately -500 mASL to at least the area of Pad C. Smaller secondary outflows may flow to the NW toward Pad D.

The conceptual model was used as a point of departure for the 3-D numerical natural state model described in the following sections. The numerical model was calibrated by matching feedzone pressures and temperature profiles in A-pad wells. The calibrated numerical model was used to derive a preliminary estimate of the production capacity of the reservoir intersected by A-pad wells.

2. COMPUTATIONAL VOLUME, MODEL GRID, FORMATION PROPERTIES, AND BOUNDARY CONDITIONS

The ground surface elevation in the Sorik Marapi area varies from less than 300 mASL (meters above sea-level) to over 2100 mASL. The bottom of the deepest well drilled in the A-pad area (A-102) is at about -1229 mASL. The bottom of the model grid is placed at 2500 m below sea-level; thus the model grid extends about 1300 m below the deepest well. The top of the model grid is placed at the assumed water level (1 bar surface). An overlay of the areal grid (area 13 km by 10 km) over the Sorik Marapi geothermal field is shown in Figure 3. The origin of the grid is at 564,432.5 mE and 69,180.5 mN. The grid is rotated to align with the main geological features. The x-direction is oriented 32.71 degrees north of east; the y-direction is 32.71 degrees west of north. The x and y co-ordinates are aligned along the northeast-southwest and northwest-southeast directions, and the z-co-ordinate is directed vertically upwards.

The model volume is divided in to 26x32x27 grid blocks in the x- and y- and z-directions respectively. Grid block numbers in the x, y, and z directions are denoted by I, J, and K, respectively. In the x- and y-directions, grid blocks range from 200 m to 500 m in size; the larger grid blocks (500 m) are used along the model boundaries. The fine grid blocks (200 m) are used to cover the region where the majority of the wells are located. In the z-direction, the grid blocks range are either 500 m or 100 m; the two 500 m grid blocks are deployed along the bottom boundary. The vertical grid in the x-z plane is displayed in Figure 4.
Figure 1: Location of current (2019) well pads and well tracks. At the time (2017) the numerical model was developed, only data from A- and E-pad wells were available. Cross-section (AA’) shown in Figure 2 is based on information available in 2017.

Figure 2: A NW-SE cross section through Area 1.
Garg et al.

Figure 3: Model grid in the x-y (horizontal) plane. Only A- and E-pad well tracks are shown.

Figure 4: Vertical grid (x-z plane) used in numerical simulation.

The 3-D numerical model was constructed using STAR geothermal reservoir simulator (Pritchett, 2013). Formation properties utilized for the natural-state model are given in Table 1. Many of the formation properties (e.g. intrinsic rock density, thermal conductivity, porosity) are based on published data for similar rocks. Rock types assigned to individual grid blocks are based on lithological model based on drilling logs. During the development of the natural-state model, the boundary conditions (i.e., heat and mass fluxes along the bottom boundary, pressure specification along the top boundary) and the formation permeabilities were freely varied in order to match the observed feedzone pressures and temperature profiles in wells. Seventeen such calculations were carried out; in the following, we will only describe the final case. A cross section of the grid with the rock formation types assigned to each grid block is displayed in Figure 5.
Table 1. Rock Formation Properties.

<table>
<thead>
<tr>
<th>Formation Name</th>
<th>Intrinsic rock density (kg/m³)</th>
<th>Rock grain specific heat (J/kg·°C)</th>
<th>Global Thermal Conductivity (W/m·°C)</th>
<th>Porosity</th>
<th>Permeability in x-direction (mdarcy)*</th>
<th>Permeability in y-direction (mdarcy)*</th>
<th>Permeability in z-direction (mdarcy)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sorik Volcanics</td>
<td>2800</td>
<td>1000</td>
<td>1.5</td>
<td>0.10</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>2. Roburan Volcanics</td>
<td>2800</td>
<td>1000</td>
<td>3.0</td>
<td>0.10</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>3. Sibanggor Volcanics</td>
<td>2800</td>
<td>1000</td>
<td>3.0</td>
<td>0.10</td>
<td>1</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>4. Sibanggor-upflow</td>
<td>2800</td>
<td>1000</td>
<td>3.0</td>
<td>0.10</td>
<td>1</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>5. Sibanggor-reservoir</td>
<td>2800</td>
<td>1000</td>
<td>3.0</td>
<td>0.10</td>
<td>20</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>6. Roburan-reservoir</td>
<td>2800</td>
<td>1000</td>
<td>3.0</td>
<td>0.10</td>
<td>20</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>7. Sorik-reservoir</td>
<td>2800</td>
<td>1000</td>
<td>1.5</td>
<td>0.10</td>
<td>20</td>
<td>20</td>
<td>2</td>
</tr>
</tbody>
</table>

*It is assumed that 1 millidarcy is exactly equal to $10^{-15}$ m².

Figure 5. Assignment of formation types/properties. Green (3,4,5): Sibanggor volcanics, Brown (2,6): Roburan volcanics, Yellow (1,7): Sorik volcanics, White: above local ground surface. Grid-blocks above the assumed 1-bar surface are tagged by index 0.

The upflow zone ($i=5; j=20, 21$) is located to the west of A-pad wells, and is designed to simulate deep hot water influx from the west. The top of the upflow zone is placed at -300 mASL. Along the top boundary, the water table (i.e. 1 bar surface) is assumed to be at an elevation

$$z_w = \text{minimum (480, } z)$$

(1)
where $z_w$ denotes the water table elevation (mASL) and $z$ is the local ground surface elevation.

The ground surface temperature and shallow subsurface temperature gradient are assumed to be 20 °C and 60 °C/km, respectively. If the water table given by Eq. (1) falls below the mid-point of a grid block, the grid block is flagged as void. Sources and sinks are imposed in all the top-most grid blocks in each vertical column to maintain the pressures and temperatures consistent with Eq. (1), and the assumed surface temperature and shallow subsurface temperature gradient. Thus, both mass and heat flux are allowed along the top surface. Other than the prescribed upflow along the bottom boundary, all mass influx or outflow takes place along the top model boundary. Along the bottom boundary, a uniform conductive heat flux of 300 mW/m² is imposed along the entire surface. In addition, a uniformly distributed mass flux (total mass flow = 60 kg/s, internal energy = 1354.3 kJ/kg) is imposed along the bottom of the grid at $i=5, 6$ and $j=20, 21$. The available temperature data for A-pad wells indicates temperature inversions in most wells; therefore, it is likely that the A-pad wells are located in an outflow zone. The assumed upflow zone lies to the west of A-pad. All the vertical faces of the grid are assumed to be impermeable and insulated.

The reservoir fluid is treated as pure water.

3. COMPUTATION OF QUASI-STEADY NATURAL STATE

Starting from an essentially arbitrary cold state, the computation was marched forward in time for about 500,000 years. The maximum time step used was 50 years. After about 300,000 years, the changes in total thermal energy and total fluid mass in the grid are quite small over a time scale of 50 to 100 years. The computed temperature and pressure values at cycle 10,000 (about 500,000 years) were compared with the available data.

The computed feedzone pressures at cycle 10,000 are compared with measured static values in Figure 6. Although the pressure data display some scatter, the fits to measured and computed values are in excellent agreement. The close agreement between the two fits shows that the vertical temperature distribution (and hence the pressure gradient) is correctly reproduced by the model. The measured temperatures in two A-pad wells are compared with calculated results from the model in Figures 7-8. The computed temperature profiles for these wells are in reasonable agreement with the measurements; similar agreement was obtained for other A-pad wells.
Figure 7. Comparison of measured temperature profile (green) with computed profile (red) for well A-103. The downhole temperature survey was recorded on June 7, 2017 (shut-in time: about 6 days after a discharge test).

Computed temperatures at sea-level (about 900 m depth) are displayed in Figure 9. In the drilled area, temperatures are seen to be highest in the A-pad area, and decline to the north (D-pad area), south (C-pad area) and east (P-pad area). The computed temperature trends, but not the absolute values, are consistent with recent (2019) data from C-, D- and P-pad wells.

Figure 8. Comparison of measured temperature profile (green) with computed profile (red) for well A-104. The downhole temperature survey was recorded on September 23, 2017 (shut-in time about 41 days after a discharge test).
4. PRODUCTION CAPACITY OF A-PAD WELLS

Based on productivity indices computed from short term discharge tests and the above-described natural state model, three production/injection scenarios were run to assess the production capacity of three A-pad wells, i.e., A-101, A-103, and A-104. All the three scenarios involved discharge of A-101, A-103, and A-104 with injection of 80% of the produced mass into wells A-102 and A-106. The model computations indicated that it should be possible to sustain a discharge rate of about 700 tph for 20 years.

5. UPDATE FROM RECENT DRILLING AND TESTING

Since the numerical reservoir model was developed in 2017, well drilling and testing has continued at Sorik Marapi, including 3 wells from Pad D, 5 wells from Pad C, and one well from Pad P. Drilling and test data from C-pad wells indicates that A-pad and C-pad wells intercept the same ~240 to 290 °C reservoir. The C-pad wells are, however, generally lower in temperature than A-pad wells consistent with upflow closer to Pad A. Initial evaluation of the geology and thermal regime of the wells drilled from D- and P-pads indicate that these are outside the >240 °C reservoir intersected by Pad A and C wells. Based on ongoing reanalysis of drill cuttings and well test data, it appears that the Great Sumatran Fault forms a permeability boundary on the northeast side of the reservoir. Additional drilling is planned from T-pad located in between A- and C-pads and will further define the western and eastern boundaries of the reservoir. Although the temperature distribution pattern computed from the natural state model described in Section 3 is in accord with data from newer wells, quantitative differences point to the need for updating the numerical model taking into account the testing results from newer wells.

REFERENCES