Zero Generation of Muara Laboh Numerical Model: Role of Heat Loss and Shallow Wells Data on Preliminary Natural State Modeling

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**Keywords**

Geothermal exploration, Muara Laboh Indonesia prospect, heat loss survey, numerical modeling, temperature distribution, well placement

**ABSTRACT**

During a prefeasibility study conducted at the Muara Laboh geothermal prospect, geology, geochemistry, and geophysics (3G) data were acquired to define resource size, concession area boundaries, and to serve as input to a development plan to assess the project cost and project economics. In addition to 3G data, a heat loss survey was conducted to provide undisturbed heat flow of the geothermal system. A conceptual model of Muara Laboh was constructed and a numerical model was built on STARS-CMG constrained by heat loss and data from shallow wells. The model was used to estimate subsurface temperature distribution, to estimate the location and thickness of the outflow tongue, and to assist in defining well pad locations during the exploration stage.

**Introduction**

The Muara Laboh geothermal prospect is located in Sumatra, Indonesia, within the Suliti segment (95 km long) which represents one of the dilatational right offset segments along the Great Sumatera Fault (GSF) Zone (Figure 1). These offsets along the GSF are often the focus of the active volcanic centers. The GSF structure has proven to be a high permeability zone for geothermal systems as shown by the Sarulla geothermal field. Besides high permeability, the GSF may also provide multiple conduits for magma to move up from depth and provide a heat source the geothermal system.

A prefeasibility study completed by Supreme Energy in 2008 has indicated the occurrence of a high temperature geothermal reservoir at Muara Laboh that could support development of 220 MWe power plant for 30 years. Geoscientific data assessment has demonstrated that the Muara Laboh geothermal prospect is a liquid dominated reservoir system with a temperature range of 210-320°C. The Muara Laboh conceptual model was constructed with a heat and mass source located beneath Patah Sembilan summit. The hydrology of the geothermal system indicates a vertical upflow zone flow beneath Patah Sembilan and the Idung Mancung area, and flow laterally to the north where the expected temperature reversal is occurred. This outflow area is toward the Balun area, another prospect with a separate geothermal system. The conceptual model has shown that most of the Muara Laboh upflow area is located within protected forestry area, and as a consequence there is a risk of the expected proven area associated with outflow location.

To better understand the risk and to guide a targeted exploration well, a heat loss survey to measure total heat flow was carried out. The result of the heat loss measurement is used to constructed numerical model of Muara Laboh prospect. This zero-order numerical model is used as a fundamental tool to

![Figure 1. Location map of Muara Laboh prospect.](image)
further investigate the outflow location and thickness of the outflow tongue. Knowing the anticipated location of the outflow, an exploration strategy and well targeting program was constructed by taking into account the uncertainties associated with subsurface temperature distribution and nature of the fault system that provide permeability for fluid flow.

A numerical model of the Muara Laboh geothermal prospect was built on STARS, an advanced process and thermal reservoir simulator developed by Computer Modeling Group (CMG) Ltd. based on conceptual model. The heat and mass source for the model is based on the result of heat loss survey. The estimated resource temperature from the geothermometer and the shallow well data were used to calibrate the model. The result of the simulation has indicated the proposed exploration area to prove 220 MWe is located within safe margin area with economical depth and enough to sustain the production for 30 years.

Geologic Setting

The Muara Laboh prospect is located at the southeastern end of the Suliti segment (95 km long) of the dextral strike-slip GSF system. In general, geothermal systems associated with the GSF are related to two types of structural settings: fault grabens commonly located along the fault, and dilatational areas located at the ends of fault.

The northwest end of the segment terminates at a 4 km-wide offset at Danau Atas and G. Talang, and the southeast end terminates at a 4 km-wide offset on the western flanks of G. Kerinci. This zone is likely to be a fault graben splay system or dilation-extension zone that will provide very high permeability and a zone of weakness for intrusive and volcanic activity (heat source), which is a perfect setting for a large geothermal system.

Resource Temperature

Pertamina drilled three temperature gradient wells in 1992 to early 1993 – MLB-1, MLB-2, and MLB-3 – to depths of 275m, 250m, and 225m, respectively. The maximum temperature in each of the holes was 44°C for MLB-1, 68°C for MLB-2, and 36°C for MLB-3. During drilling, there was a shallow lost circulation zone encountered in MLB-2 starting at 101 m and extending to total depth, but there was no significant temperature gradient in the MLB-3 well. All the gradient wells were plugged and abandoned.

The calculated geothermometers are presented in Table 1. Geothermometry can be applied with most confidence to the high-chloride spring waters of Sapan Malulong. Geothermometry is not considered applicable to the bicarbonate springs or the acidic waters from the steam heated thermal areas. In both cases the chemistry is developed near the surface and only provides an idea of possible source water temperatures.

Conceptual Model

The conceptual model of the Muara Laboh geothermal system attempts to describe hydrology (up-flow to out-flow), discharge-recharge of the system and fluid transport.
characteristics. Key elements of the conceptual model are directly related to the geology and tectonic setting interpreted from the data acquired from the pre-feasibility study. Fluid chemistry, MT, gravity, and local stratigraphy constraint the interpretation. The conceptual model is used as the base to calculate resource potential, to construct an exploration strategy including well targets, risk assessment, drilling sequence, and to develop a mitigation plan.

The hydrology of the Muara Laboh system reflects the proximity of a volcanic heat source beneath Patah Sembilan based on the type and chemistry of the surface manifestations. There is a superheated fumarole on the high land associated with Patah Sembilan with an outflow to a boiling high flow chloride spring at Sapan Malulong on the lowland. Although the distance between the two features is quite long, we estimate that the heat source may be closer to Sapan Malulong (Figure 3).

**Heat Loss**

Heat loss from the Muara Laboh geothermal prospect was measured in May 2011 in an area reaching from the southern area of Patah Sembilan to Sapan Malulong, about half of the resource area. The southern area was dominated by steaming ground, mud pools, and fumaroles typical of geothermal system manifestations. Fumarole activity at the Idung Mancung and Patah Sembilan areas included superheated steam discharges (>100°C). The manifestations in the central area were predominantly hot water discharges with temperatures in the range of 50-98°C. Measurements were made of the areal extent of thermal and steaming ground, temperature of fumaroles, and temperatures of pools and fluids at springs.

The total measured heat loss from the Muara Laboh south resource was calculated to be approximately 104 MWth. The total heat loss from the southern manifestations was measured at approximately 68 MWth. This equates to a mass flow of steam of 26 kg/s. The measured fumarole heat flow (20 MWth) did not include all steam vents (some were inaccessible) and the total from these unmeasured features is believed to be greater than that measured. Total heat loss from the central manifestations was measured at approximately 36 MWth which equates to a mass flow of 108 kg/s of 98°C water. Modeling of the steam separation processes indicates that the distribution of steam and water could be reasonably produced with typical reservoir processes, such as boiling of 280°C upflow water down to 200°C. Figure 4 shows a tentative model of the Muara Laboh heat loss.

**Numerical Model**

**Model Setup**

The model was built on the STARS-CMG simulator and covers an area of 8.5 km x 13.7 km from Patah Sembilan (PS) to Sapan Malulong (SM). This area represents about half of the total Muara Laboh concession area. The vertical extent of the model is from +1,250 m-asl down to -2000 m-asl. The orientation of the model was adjusted so that is parallel to the orientation of Great Sumatra Fault zone structure in NW-SE direction. The reservoir is represented as a three-dimensional single porosity model consisting of a 50 m x 50 m grid size with thickness varying from 50 m (surface to -1000 m-asl) and 200 m (-1000 m-asl to -2000 m-asl). It is discretized into 75 layers with area of 145 by 274 blocks giving a total of 2,979,750 blocks. There are 1,661,976 active blocks and the remainder are NULL blocks (one that has zero porosity but contain rock thermal properties to simulate the conductive heat loss).
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Boundary Condition

The top of the reservoir (TOR), the cap rock, is constructed based on the combination of the magnetotelluric data and geothermometer data. It represents the upper no flow type boundary. Lateral boundaries of the model are impermeable to fluid flow. A constant boundary condition type is applied at the top of the model to represent atmospheric pressure, and is set at constant temperature and pressure of 25°C and 1 bar respectively. A uniform heat flux was imposed at the bottom layer, while heat loss is allowed through the upper boundary via conduction. In addition, a spring serves as natural discharge at a constant rate at the top of the reservoir. The location of the natural discharge is associated with the surface manifestation location, and the amount of natural discharge is estimated using heat loss measurements.

Initial Condition

The model was initially developed as a single liquid system in gravitational equilibrium with all boundaries impermeable to fluid flow, and was initialized with cold liquid of 25°C with water saturation of 100% heated to reach steady-state condition. Corey’s curve (1954) was chosen for relative permeabilities with linear capillary function. The following parameters were held constant in all simulation performed: matrix porosity of 5%, rock heat capacity of $1.56 \times 10^6 \, \text{j/m}^3/\degree\text{C}$, and rock thermal conductivity of $1.81 \times 10^5 \, \text{j/m/day/\degree\text{C}}$.

Model Calibration

Normally the calibration process of a geothermal numerical simulation is carried out in two steps: natural state and history matching. The calibration process was done by matching calculated parameters with measured parameters representing the reservoir changes in pressure, temperature and enthalpy due to fluid withdrawal from a production well. However, as there is no information or no hard data representing the reservoir, the calibration process is carried out by adjusting the amount of heat and mass source feeding the reservoir so that the generated temperature and its lateral gradient are constrained by temperature gradient from the temperature gradient well data for shallow depths and calculated geothermometer temperatures for deeper depths.

In the initial run, the model was heat up with heat flux according to the heat loss measurement. A constant heat and mass source equal to $2.5 \times 10^{-3} \, \text{kg/s/m}^2$ at enthalpy of 1,300 kJ/kg was set at the bottom layer beneath Patah Sembilan area. The steady state result indicates cooler temperatures compared to geothermometer-derived temperature distribution. The amount of heat flux was then adjusted to about 20% higher than measured heat loss and the result indicated a good agreement between model results and geothermometers. The shallow temperature also shows reasonable agreement between model results and measured temperature, see figure 7. The mismatch for MLB-1 and MLB-3 wells is due to unstable temperature measurement (only measured at day one heating up period). The calibration process does not include permeability modification.

Natural State Simulation Result

Pseudo-steady-state result was obtained after a simulation time of 50k years. Figure 8 shows the pseudo-steady-state temperature distribution at -200 m-asl elevation. The temperature gradient shows the fluid is moving upward vertically at Patah Sembilan and continues laterally to the northwest toward Sapan Malulong. Lateral temperature gradient at +800 m-asl and -280 m-asl depth shows...
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A comparable temperature profile to temperature geothermometer (see figure 8 and 9). Vertical temperature gradient from several cross section were shown by figure 10. At upflow zone area (figure 10b) the heat and mass source established at the bottom of the layer produces a mushroom shaped temperature profile and outflow is directed to the northeast. As expected, the highest temperature gradient around the upflow area is located below the Patah Sembilan fumaroles. The NW-SE cross-section temperature profile shown in Figure 10c indicates a resource temperature of about 220°C and a temperature reversal beneath Sapan Malulong. This might indicate that Sapan Malulong is a margin area or boundary of the resource.

**Discussion**

During the exploration stage and without direct information or hard data from the reservoir, the risk associated with knowledge of the resource temperature is considered critical and must be minimizing prior to drilling an exploration well. While surface manifestation data provide an excellent sample for geothermometer calculations, there is inherent risk associated with using those data to estimate actual subsurface resource temperature. Geothermometer calculations give temperature estimates without knowing the resource depth associated with it. This fact introduced another risk on drilling targeting, i.e.

![Figure 8. Temperature distribution at -200 m-asl.](image)

![Figure 9. NE-SW lateral temperature gradient.](image)

![Figure 10. Steady state vertical temperature profile.](image)

depth of the reservoir, despite the commonly used MT survey to describe the top of the reservoir. It could be that it represents relict alteration and the cap rock/clay cap might not associated with high temperature resource, or the resource is cooling and the temperature at cap rock level is lower than the temperature definition for high temperature geothermal resource (≤ 220 °C). Numerical modeling offers a solution to mitigate the risk associated with resource temperature.
Numerical modeling at the exploration stage without hard data from the reservoir gives a poorly constrained model result and is not common practice. However, the background heat flow of the entire region provides significant information that directly relates to the naturally convecting system. The amount of the heat flux feeding the reservoir system can be estimated from the total heat flow measured at the surface or near surface. It consists of conductive losses at shallow ground, convective losses through thermal manifestation as well as radiation losses. At the Muara Laboh geothermal prospect, a heat loss survey was carried out as part of the exploration program and the result is used to set up the numerical model, called ‘zero generation numerical model’ to investigate mainly the temperature distribution of the resource, boundaries of the resource and depth of the reservoir. The resource boundary will define an exploration area to prove the resource according to the economic scale of development. The depth of the reservoir provides information for well design and drilling program.

Adjusting the heat source as much as 20% higher than measured heat flow provides enough flux to sustain the steady state thermodynamic condition of the resource. The reasonable agreement between temperature gradient wells data, model results, and geothermometry provides a foundation for model robustness. The original well trajectories were shifted accordingly based on the model result to target sweet spot area. We continue to improve the model sensitivity to permeability (matrix/fracture permeability ratio) as well as other thermal rock properties. Results will be used to fine-tune exploration well drilling targets.

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References


