Evaluation of Water Produced from a Steam Dominated System, a Case Study from the Darajat Field

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ABSTRACT

Darajat is unusual as it is one of the few steam-dominated geothermal systems in the world. Current thinking indicates that the reservoir brine in this geothermal system is deeply located and has not been accessed yet, and therefore, liquid is unlikely to be produced from the existing production wells. DRJ-CA, drilled in early 2008 in the central part of the field, is an enigma because it produces liquid.

Pressure-Temperature (PT), Pressure-Temperature-Spinner (PTS), and Tracer Flow Test (TFT) data showed that a maximum of ~74 kg/s of liquid with an enthalpy of 916 BTU/lb is being produced from this well both through shallow and deep entries. Two permeable entries just below the production casing are the suspected sources of the liquid but the exact location liquid entry is quite difficult to delineate because of the nature of these two feed zones. The deep liquid feed zone is at saturation temperature and is believed to flash to steam and very unlikely to contribute to liquid at the surface. To prevent liquid to be carried over into the steam pipeline, DRJ-CA is operated at high Flowing Well Head Pressure (FWHP).

Geochemical analysis of Down Hole Samples (DHS) indicates that the liquid encountered by DRJ-CA is typical of steam-heated groundwater above or outside the reservoir with significant silica content. This suggests that there may be Marginal Recharge (MR) down flow in this part of the field. A complication with this hypothesis is that power plant condensate has been injected in both shallow and deep wells right at the center of the field. Three hypotheses are postulated to explain the source of the liquid in DRJ-CA, namely injected condensate, MR entry into the reservoir, or a combination of both. The recent strategy to move infield condensate injection to the northeastern edge of the field should help further narrow the source of the DRJ-CA liquid.

1. INTRODUCTION

The Darajat geothermal field is located about 150 kilometers southeast of Jakarta in West Java, Indonesia at an elevation of 1,750–2,000 m Above Sea Level (ASL) (Figure 1). It is situated on the eastern side of Mt. Kendang which is part of a NE–SW-trending Quaternary volcanic range in West Java. There are numerous eruptive centers within this mountain range and numerous volcanic activities occurred, for example, at the Papandayan Volcano in 1772 and in the Guntur Volcano in 1840.

Darajat is one of the largest vapor-dominated geothermal fields in the world with a current total capacity of 271 MWe, accommodated by three power plants (Units I/II/III). PT. Indonesia Power owns and operates Unit I with a generation of 56 MWe, while Units II/III (with 94 MWe and 121 MWe of generation, respectively), are operated by Chevron Geothermal Indonesia.

Figure 1: Location of the Darajat Geothermal Field in relation to other cities in the Java Island.

The most significant structural feature in this area is the Kendang Fault which strikes northeast from Darajat along the high axis of the volcanic range, disappearing on the north side of the Kamojang field, another steam-dominated geothermal system about 10 km
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away. To the west of the Darajat field, the Kendang Fault is slightly offset by the Gagak Fault, which is considered to control major permeability within the field (Figure 2).

Figure 2: Map showing the Darajat geothermal field. Also shown are the locations of DRJ-CA and other wells mentioned in this paper. The red shaded area is the interpreted extent of the shallow perched aquifer, while the numbers show the temperature of fluid in the shallow perched aquifer measured in wells.

Since the first investigation in the early 1970’s, Chevron Geothermal Indonesia has drilled 49 wells in seven development and make-up drilling campaigns; the last make-up drilling campaign was during 2009–2011. These include 43 development, production, and injection and six slimhole observation wells. Historically, four wells have produced liquid since the first test in the late 1970s, namely DRJ-B, DRJ-C, DRJ-E, and the recent DRJ-CA (Figure 2).

During the development phase of the Darajat field, DRJ-B and E were utilized as observation wells, while DRJ-C was used for injecting the power plant condensate from Unit I. DRJ-CA, the main subject of this paper, was drilled in February 2008 along a NW direction at a moderate inclination. It was designed to produce steam from the good permeability region between the Gagak and Cibeureum Faults. The top of the reservoir encountered by DRJ-CA was defined at about 720 m ASL; this is relatively shallow compared with other neighboring wells. Based on the injection testing after well completion, DRJ-CA was estimated to produce about 17 kg/s (~8 MWe) of steam at 16 bara Flowing Well Head Pressure (FWHP).

Right after completion, the DRJ-CA heat-up data showed temperature reversals at, from top to bottom, 1,700 m ASL, 1,500 m ASL, 1,400 m ASL, 400 m ASL, and 50 m Below Sea Level (BSL) (Figure 3). The shallower temperature reversals above 1,400 m ASL were interpreted to be related with the shallow aquifer recently mapped in Darajat. The reversals at about 400 m ASL, near the production casing shoe, and at 50 m BSL were suspected to be related with cold fluid influx. Liquid production was first observed during the flow test in July 2008 and a later Tracer Flow Test (TFT) showed 1.5–9.3 kg/s of liquid was being produced from this well at 18–21 bara FWHP. DRJ-CA was eventually flowed to the system with 5 kg/s of steam at 23 bara FWHP; at this higher FWHP, the well produces dry steam.

The discovery of produced liquid at DRJ-CA was unexpected. Current thinking indicates that the reservoir brine in the Darajat geothermal system is located deep and has not been accessed by any wells. Therefore, it is unlikely to be produced from the existing production wells. Possible sources of this liquid may be the infield condensate injected at injectors DRJ-AE and C, entry of Marginal Recharge (MR) into the reservoir, or a combination of both. In addition, some wells, such as DRJ-B, C, and E, produced liquid in the 1980s, while there was no infield injection yet suggesting that MR appears to be the source of liquid at Darajat. This paper further discusses the reservoir processes that may be responsible for the presence of liquid in Darajat.
Figure 3: Chart showing heat-up PT data of DRJ-CA. Note the temperature reversals at about 1,400 m ASL, 400 m ASL, and 100 m BSL. Also shown are the kaolinite and argillic alteration zones (blue-shaded region) encountered by the well.

2. TAGGING THE PRODUCED LIQUID AT DRJ-CA

2.1. Pressure-Temperature-Spinner (PTS) Analysis

To get a better understanding of well deliverability and reservoir characterization, an initial series of well testing program was conducted at DRJ-CA. PTS analysis in 2009 indicated liquid feed zones near the production casing shoe and near TD (Figure 4). Most of the mass produced by DRJ-CA comes from the permeable steam entries at 3,500’–4,000’ MD. However, the exact location of where the liquid enters near these two feed zones could not be clearly defined from the log data. Currently, both feed zones are considered as liquid entries (Figure 4). The liquid produced by the bottom permeable entry at 6,500’ MD is at saturation and does not contribute significantly to the total well deliverability. This liquid probably flashes to steam as it enters the wellbore and is unlikely to contribute much liquid (and mass) at the surface.

Figure 4: Chart showing the permeable entries encountered at DRJ-CA during an injection/flowing PTS. The feed zones at 3,500’–4,000’ MD are suspected to produce liquid although the log data cannot distinguish which particular feed zone the liquid is coming from. The produced liquid from the bottom permeable entry probably flashes and does not contribute significantly to total well deliverability at the surface.
In terms of productivity, DRJ-CA is not a good production well. This well exhibited slow recovery after a Minimum Quenching Rate Test, unlike other Darajat steam producers. The slow heat-up indicates that this well reached saturation after 36 days of injection and was ultimately confirmed by the production test which showed that this well has an initial production of about 17 kg/s at 16 bara. This production rate is significantly less compared with the other Darajat wells drilled during that time. DRJ-CA was first put on production almost a year after its completion in December 2008 and produced at about 5 kg/s at 23 bara FWHP. This pressure was considered as the minimum FWHP to avoid liquid production from this well.

2.2. Hydrothermal Alteration
Analyses of hydrothermal alteration, temperature anomalies, and the location of shallow permeability have delineated a shallow aquifer at Darajat (Rohrs et al., 2009). This aquifer is believed to exist in the southeastern portion of the field and probably flows northeast towards the Cibeureum and Toblong hot spring areas, passing through the DRJ-B location (Figure 2).

Reservoir steam at the fumarolic areas produces acidic fluids when the fumarolic steam condenses and mixes with local ground water. The ground water possibly becomes acidic as H₂S (entrained in the steam) is oxidized to form acid-sulfate fluid; further fluid-rock interaction leads to the formation of secondary hydrothermal alteration minerals, such as kaolinite, alunite, etc. At Darajat, the perched steam condensate may have been “acidified” with the continuous introduction of H₂S entrained in the steam. Although this process commonly occurs in a geothermal system, the acid nature of this perched aquifer is still questionable because no sample has been collected at the suspected depth of the shallow perched aquifer.

Post-drilling data show that DRJ-CA demonstrated some evidence for the existence of a shallow perched aquifer as characterized by temperature reversals and secondary kaolinite at 1,545–1,114 m ASL (Figure 3). However, this shallow perched aquifer encountered by DRJ-CA is relatively deeper compared with its neighboring wells (Figure 5).

Figure 5: 3D cross-section showing the shallow aquifer encountered by DRJ-CA and other neighboring wells. Note that the shallow aquifer deepens towards the north as intersected in DRJ-CA. The color represents the temperature of the shallow aquifer as measured in wells.

2.3. The Clay Cap Above the Reservoir
Typical of other geothermal systems, the rocks that cap the Darajat geothermal system are altered to secondary clays. These clays vary from smectite (stable at ≤180ºC), mixed-layered illite-smectite or smectite-chlorite, etc. A re-interpretation of the Magneto-Telluric (MT) data at Darajat using the 1D invariant mode defined the location of the 10 ohm-m clay-altered rocks that overlie the geothermal system (Figure 6). The distribution of the low resistivity (Figure 6) and mineral alteration (Figure 3) indicates that the clay cap distribution is consistent. The perched aquifer appears to be located within the clay cap.

Figure 6: Cross section A-A’ showing the clay cap (green shaded area) distribution atop the Darajat reservoir.
2.4. Fluid chemistry

The chemistries of both produced liquid and down hole liquid samples at DRJ-CA are very distinctive when compared with the power plant condensate injectate, steam condensate collected at drain pots (DPs) and other low point drains (LPDs) along the steam pipelines, and surface water (Table 1). However, the DRJ-CA produced liquid is similar to the Awibengkok shallow leak liquid. Condensate injectate can be distinguished from other fluids by its neutral pH, and low SiO$_2$, low HCO$_3$ and relatively higher SO$_4$ contents. Liquid from DPs and LPDs show extremely high B with 5–6 pH; the high B content can be explained by continuous boiling from flowing steam to static condensate liquid which accumulates at the bottom of the pipeline. Surface water, which does not undergo significant water-rock interaction, has low SiO$_2$, B, SO$_4$ and HCO$_3$ contents with neutral pH. In the geothermal reservoir, the produced liquid is characterized by high SiO$_2$, high SO$_4$, high HCO$_3$, and relatively high B contents and normal to basic pH values like the Awibengkok shallow leak liquid (Table 1).

<table>
<thead>
<tr>
<th>Liquid Type</th>
<th>Boron (mg/kg)</th>
<th>SiO$_2$ (mg/kg)</th>
<th>SO$_4$ (mg/kg)</th>
<th>HCO$_3$ (mg/kg)</th>
<th>Cl (mg/kg)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensate Injectate</td>
<td>15 – 57</td>
<td>0.5 – 2</td>
<td>45 – 90</td>
<td>&lt; 16</td>
<td>0</td>
<td>6 – 7</td>
</tr>
<tr>
<td>Condensate Pot</td>
<td>60 – 1150</td>
<td>0.5 – 32</td>
<td>0.2 – 31</td>
<td>2 – 5</td>
<td>0</td>
<td>5.5 – 6.5</td>
</tr>
<tr>
<td>Low Point Drain</td>
<td>1200 – 1500</td>
<td>20 – 50</td>
<td>2 – 5</td>
<td>6 – 6.5</td>
<td>0</td>
<td>5 – 6</td>
</tr>
<tr>
<td>Surface Water</td>
<td>&lt; 1</td>
<td>14 – 17</td>
<td>3.5 – 4</td>
<td>9 – 12</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Awibengkok Shallow Leak Liquid</td>
<td>9</td>
<td>168</td>
<td>550</td>
<td>103</td>
<td>186</td>
<td>6</td>
</tr>
<tr>
<td>DRJ-CA DHS</td>
<td>164</td>
<td>505</td>
<td>340</td>
<td>102</td>
<td>6 – 200</td>
<td>7</td>
</tr>
<tr>
<td>DRJ-CA Liquid (Surface Sampling)</td>
<td>3 – 250</td>
<td>150 – 600</td>
<td>150 – 600</td>
<td>150 – 400</td>
<td>30 – 65</td>
<td>6 – 9</td>
</tr>
<tr>
<td>DRJ-CA, DRJ-B, DRJ-E</td>
<td>5 – 100</td>
<td>400 – 1000</td>
<td>150 – 500</td>
<td>90 – 250</td>
<td>30 – 150</td>
<td>7 – 9</td>
</tr>
</tbody>
</table>

Table 1: Chemistries of possible Darajat liquid source compared with the Awibengkok shallow leak liquid

If the produced liquid at DRJ-CA is from the injected power plant condensate, the condensate must have reacted with the reservoir rocks to acquire elevated concentrations of Na, K, Ca, SiO$_2$, and Cl. This reaction is further complicated by the fact that condensation and mixing with the fluid that has reacted with the rocks should also generate large amounts of dissolved B, HCO$_3$, and SO$_4$. The reactive history of the condensate injectate metamorphosing into the produced liquid at DRJ-CA would require opposing reservoir processes, i.e., mixing of two liquids and equally important constant exposure to “fresh” reservoir rocks that are not coated by reaction products of the liquid–rock interaction.

Three reservoir processes are required to explain the chemical conversion from condensate-type to a liquid similar to that of DRJ-CA, and these processes are as follows:

- NCG influx: significant increase in dissolved SO$_4$ and HCO$_3$ requires high flux of NCG through the liquid (e.g., bubbling and condensation);
- Sustained boiling: significant increase in dissolved B requires sustained boiling/evaporation of liquid to concentrate B in liquid (e.g., steam/liquid fractionation); and
- Water-rock reaction: significant increase in SiO$_2$ requires sustained reaction of dilute liquid with rock/clays (e.g., enhanced by low pH and/or high temperature).

The produced liquid and DHS chemistry of DRJ-CA plot in the steam-heated water portion of the Cl-SO$_4$-HCO$_3$ ternary diagram (Figure 7). The chemistry of this liquid was also compared with the Awibengkok shallow leak liquid sample (a possible perched aquifer liquid at Awibengkok) and condensate injectate liquid from the Darajat injectors. All of the condensate chemistry plots at the SO$_4$ apex. The condensate injectate is depleted in HCO$_3$ compared with the produced liquid from DRJ-CA. The presence of chloride and other chemical species in the DRJ-CA liquid indicate that this liquid is not directly related to the injected power plant condensate.
Figure 7: Ternary plot of Cl-SO$_4$-HCO$_3$ showing the liquid chemistry from surface discharge and DHS at DRJ-CA. Red circles represent surface samples while green triangles are DHS. Also shown is the Salak shallow leak liquid for comparison. The liquid chemistry matches with steam-heated water characteristics.

3. RESERVOIR MODELS TO EXPLAIN THE LIQUID AT DRJ-CA

As stated earlier, NCG influx, sustained boiling and water-rock reaction need to be incorporated into the models to explain chemical conversion of a dilute liquid to something similar to DRJ-CA liquid. Three models are proposed with each model requiring different well conditions, various liquid source/s, and different reservoir processes as described below.

3.1. Model 1: Boiling of condensate injectate

Model 1a - This end-member DHS liquid chemistry is characterized by high concentrations of SiO$_2$, HCO$_3$, and SO$_4$. Assuming condensate injectate is the source of the DHS and the well is in flowing condition, the sequence of the reservoir processes that should occur is (1) water-rock/clay reaction, (2) condensation, and (3) boiling which occurs along the fractures during fluid migration. This model is applicable to DRJ-CA discharge liquid and other flowing scenarios. The downside of this model is the continuous source of fresh rock that will be exposed to liquid to maintain the high SiO$_2$ content (i.e., if the same rock is exposed to interaction with flowing fluids, the silica content of the rock will have been consumed after some period).

Model 1b – Similar with the above model, this end-member DHS liquid chemistry contains high SiO$_2$, HCO$_3$, and SO$_4$ concentrations. Assuming condensate injectate is the source of the liquid and the well is in flowing condition, the order of the reservoir processes that should happen is (1) condensation together with (2) water-rock/clay reaction along the fractures during fluid migration; (3) boiling of the liquid occurs at the bottom of the wellbore to enrich the SiO$_2$ and B. This model only applies to shut-in conditions, so liquid fills up the bottom of the well (or wells) which are close to the injectors (i.e., within the “cone of liquid migration”). If a well is located far away from injector, the source of the liquid should be replaced with a natural steam condensate. The downsides of this model are similar with the Model 1a above.

Figure 8: Model 1a – produced liquid has undergone continuous boiling and water-rock reaction along fracture pathways.
3.2. Model 2: Condensate injectate undergoes similar conditions as Condensate/Low Drain Pots

This model assumes that boiled condensate injectate (i.e., high B liquid) is the source of the liquid and then undergoes a CP- and LPD-like process to explain the chemical change from dilute fluid to DRJ-CA liquid type. The CP- and LPD-like process provides continuous boiling along the fractures during fluid migration to wellbore. The sequence of reservoir processes should be (1) water-rock/clay reaction in order to enrich the SiO$_2$ content, (2) condensation may happen next creating a high flux of NCG passing vertically through the fractures where liquid travels enriching both the SO$_4$ and HCO$_3$, and (3) the last process should be boiling to ensure the SiO$_2$ and B content remains high per DHS liquid results. This model appears to be limited as continued fresh rock exposure is needed to maintain the SiO$_2$ content (please refer to downsides of both Models 1a and 1b). Also, constant fracturing or re-routing of the liquid to fresh fractures would be required to allow large-scale production of this fluid type.

3.3. Model 3: MR liquid undergoes enrichment from rising NCG and downflows to the geothermal reservoir

In this model, shallow MR liquid (which may be above or within the clay cap) may experience continuous condensation as NCG passes through it. Fracture permeability allows fluid from the reservoir to escape vertically and arrive near the surface. The exposure of groundwater to reservoir NCG increases both the HCO$_3$ and SO$_4$ concentrations. As the pressure drops within the geothermal reservoir due to mass extraction, this MR liquid may enter the reservoir along the same fluid pathways originally used to “steam-heat” the groundwater. The pressure drop caused by the production wells causes the high SO$_4$ and HCO$_3$ liquid to migrate (possibly laterally) and travel down to the wellbore and intersected permeable production entries. During the lateral migration, water-rock/clay reaction and, possibly additional boiling increases both SiO$_2$ and B concentrations. These processes provide chemical conversion from dilute to a liquid similar to that produced at DRJ-CA.
Figure 11: Model 3 - MR liquid undergoes enrichment from rising NCG and downflows into the geothermal reservoir along permeable fractures.

Among these three reservoir models, Model 3 (Figure 11) is preferred because of the following reasons:

- This model does not need continuous exposure to fresh rock to maintain the high SiO$_2$ contents in flowing shallow liquids, as a small reservoir of liquid is created above the clay cap (i.e., at DRJ-CA);
- Geologic time allows this complicated conversion processes to occur outside of the reservoir;
- Chemical analogs of shallow “steam-heated” liquids exist (e.g., Awibengkok shallow leak liquid sample); and
- Other models are too complex for “real-time” chemical conversion (“Occam’s Razor Principle”).

In 2012, infield injection in DRJ-AE was moved to the edge of the field and has helped to confirm whether MR liquid or condensate injectate supplies the liquid to the production wells. A liquid similar to the previous chemistries is still being produced at DRJ-CA even after infield injection has been terminated. Therefore, a neutral peripheral/marginal liquid (e.g., perched aquifer) is believed to represent the most likely model (Model 3) to explain the presence of the liquid produced in DRJ-CA.

4. CONCLUSIONS

The multidisciplinary approach in studying the liquid produced at the steam-dominated Darajat geothermal field has assisted in defining the location of the source of the liquid produced at DRJ-CA and the possible reservoir processes responsible for this liquid. The relatively high concentrations of SiO$_2$, HCO$_3$, SO$_4$, B, and Cl and neutral pH of the produced liquid suggests that this liquid has had sufficient time to react with reservoir rocks and is probably not the injected power plant condensate. In addition, the presence of both HCO$_3$ and SO$_4$ indicate that it may be peripheral or near-surface liquid. It is believed that this liquid comes from a shallow aquifer downflowing into the Darajat reservoir.

To produce dry steam, DRJ-CA is flowed at ~16 barg FWHP. The plan forward is to put this shallow aquifer behind casing in future make-up wells, and evaluate isolating this aquifer in the existing wells.

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