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THE INTERPRETATION OF LIQUID COLUMN PRESENCE INSIDE WELLBORE IN VAPOR-DOMINATED GEOTHERMAL RESERVOIR

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ABSTRACT

There have been discussions which lead to a number of hypotheses related to the presence of the liquid column inside geothermal wellbores in vapor-dominated reservoirs. Previous hypotheses suggested that this phenomenon is due to condensation and the existence of liquid in the reservoir. The phenomenon is uncommon due to the liquid column temperature at the borehole was identified as compressed liquid. Therefore, we may not infer the liquid column is from liquid reservoir due to the temperature below the saturation temperature. Numerical study was performed to understand the physical process of this phenomenon. A coupled wellbore-reservoir model was built to simulate the mass and heat balance using TOUGH2. The model is based on a cylindrical, homogenous reservoir geometry with a wellbore located at the center of the model. Feedzone and bottomhole reservoir pressures were taken from PT Spinner survey. The well bleed-off model was built and simulated to test the condensation process. The result does not prove significant liquid volume contributed from condensation process. This result brought us to propose other hypothesis of which the liquid column is related to the involvement of drilling mud during drilling stage. Our proposed hypothesis clearly represents the real condition considering there was a good agreement between the simulated and measured pressure temperature profile versus depth. Through our data calibration, unexpectedly this study found the existence of an additional feedzone at the deeper depth which could not be detected by PTS survey due to low permeability fractured rock or minimum mass flow rate. Ultimately, the determination of the origin and process of liquid column may help having a more reliable interpretation of subsurface profile, considering the similar cases were also reported in other vapor-dominated geothermal reservoirs.

INTRODUCTION

Geothermal systems in Indonesia are mostly known as hydrothermal convection systems. They are characterized by circulation of meteoric water (natural recharge by rainfall) into depth, the presence of natural heat source, a storage or reservoir where heat transfer from heat source and fluid are processed, and natural discharge (manifestation). The systems are usually divided into two general systems based on the proportion of fluid in pore (matrix and fracture) within reservoir, namely vapor-dominated and liquid-dominated system. Vapor-dominated systems, such as, The Geysers in Northern California, Kamojang and Darajat in Indonesia, are very suitable for the electrical power production because they produce only steam, with high enthalpy, in most cases superheated. This type of reservoir is said to be rare while the more common is liquid-dominated reservoir, such as Wairakei in New Zealand, Sibayak in Northern Sumatra and Wayang Windu in West Java, Indonesia, produce the mixtures of water and steam with lower enthalpy.

The main characteristic to distinguish those types of systems is their pressure gradient. In vapor-dominated systems, the pore space is filled with steam, therefore the pressure gradient is vaporstatic. In liquid-dominated systems, the pore space is liquid-filled so it is hydrostatic. Vaporstatic is illustrated by its steep graph with very little gradient of pressure. While, the gradient of hydrostatic pressure is larger than the gradient of vaporstatic pressure.

There have been discussions which lead to a number of hypotheses related to the phenomenon of the liquid column presence inside geothermal wellbore in vapor-dominated reservoir. The presence of liquid column inside wellbore was observed by the pressure, temperature, and spinner logging tool which was lowered down into the projected depth inside wellbore. The logging tool function as an automatic data recorder measuring pressure and temperature at any given depth and is also useful to locate the sites of feed zones which supply fluid from reservoir into the wellbore. The presence of liquid column is not very common because the profile of pressure temperature deviates from its normal condition of vapor-dominated geothermal reservoir.

Some hypotheses have been proposed but yet tested quantitatively. The main one is that the liquid column may be the product of its vapor condensation which was caused by heat loss of the fluid to formation through wellbore. Other hypothesis is that the liquid column may be considered as drilling mud which was trapped at the bottom of the wellbore which becomes immobile due to highly tight surrounding reservoir with no fracture-network.

The last hypothesis is that the liquid column may be supplied by water reservoir, in other words, there may be liquid reservoir beneath vapor reservoir that makes the profile of pressure temperature accepted as two-phase reservoir. Despite the fact that there may be water beneath the vapor zone, the last hypothesis may be ignored due to PT profile which was taken from near observed well (the adjacent well) do not indicate the characteristic as two-phase reservoir. If there is water zone, then the huge area of water zone shall cover all wellbores at the same depth, thereby all of the PT profile from wellbores will indicate the same characteristic as two-phase reservoir. While, the PT profiles from the adjacent wells do not indicate the same thing. In addition to that, the liquid temperature is below its saturation temperature therefore identified as compressed liquid. This is uncommon because the near distance with heat source. However, more advanced study should be conducted to have a better conclusion.

This study presents a model of wellbore within reservoir in radial system with permeability which allows fluid to flow from permeable zone in the reservoir to wellbore through fracture zone. This study also presents a model for predicting condensation occurs inside wellbore as a function of heat loss and pressure drop. As the geothermal fluid ascends the well, the loss of both momentum and heat occurs. The consequence of the heat loss leads to steam fraction decreasing (or liquid fraction increasing). Simultaneously pressure drop leads to flashing and steam fraction increasing.

The case was observed in vapor-dominated geothermal reservoir with a temperature of about 245°C. The observed well is named as NRT-A where the liquid column was encountered at the bottom of the wellbore and as a comparison, the adjacent well, NRT-B where no liquid column presents, is also observed. Both wells show difference characterization of PT profile. NRT-A is filled with the liquid at the bottom hole up to nearly reach the deepest feed zone inside wellbore as recorded by PTS tool at bleeding or shut-in well condition. After being produced, the liquid column was not evaporated or reduced. The presumption is that wellbore is filled by the liquid when well at bleed-off or shut-in condition. This differs from NRT-B where the liquid column was evaporated and finally lost after being produced.

MODEL DEVELOPMENT

The General Aim of Modeling

The general aim of our developed model was to test our hypotheses quantitatively against observed data from a field. The model was developed under steady state and transient conditions. For steady-state condition, Homogeneous approach was used for calculating pressure drop and the heat transfer was calculated using Hasan and Kabir method. For transient condition, the study was performed with numerical solution using simulation tools. Both studies took account of fluid and heat flow.

Numerical Study

The basic idea is to set up a 3D model consisting of blocks or elements which represents the permeability structure, heat and fluid of the real reservoir with reasonable accuracy. Heat input represents the heat transfer governing the fluid flow. It is a computer program (simulator) that is able to carry out mass and heat balance calculations over a sequence the behavior of the real system. It carries out the complex mass and energy balance calculations for all the blocks in the model grid over a sequence of time steps.

Since we involve more complex calculation, TOUGH2 (Transport Of Unsaturated Groundwater and Heat) was used for building the 3D model. TOUGH2 is a simulator that widely used for modeling non-isothermal multiphase flow in fractured porous media. TOUGH2 simulator was developed for problems involving heat-driven flow[1]. It can handle coupling between flow in geothermal reservoirs and wellbores in two-phase conditions. It also provides options for specifying injection or withdrawal (production) of heat and fluids. TOUGH2 is capable to compute fluid flow in liquid and vapor phases occurring under pressure, viscous, and gravity

[1] http://esd.lbl.gov/research/projects/tough/

forces according to Darcy's law. Interference between both liquid and vapor phases is represented by means of relative permeability functions. Heat transport occurs by means of conduction (with thermal conductivity dependent on water saturation) and convection.

Our model is a cylindrical, homogeneous reservoir with a wellbore at the center. Radial flow with a reservoir thickness of 1500 meter was assumed. We do not take account of skin effects. The residual saturations were assumed 0.3 for liquid and 0.05 for steam. Grant correlation was used for relative permeability.

WELL DATA

NRT-A has 2550 meter of height with starting production liner at depth of 1002 meter. Inside diameter of production casing is of 0.222 meter. Later, the number is applied in the model as well diameter. The surrounding reservoir from top of production casing into 2550 meter is vapor-dominated reservoir, with an assumption of liquid saturation 0.3. Three feed zones were identified by PT Spinner at depth 1094, 1386, and 1740 meter. Permeable feed zones are commonly identified using pressure and temperature profile, and fluid velocity during well completion testing and heating-up. In vapor reservoir it is rare to conduct completion testing. After drilling, well is shut-in or set in bleed-off condition. The only water injection performed was during drilling. After drilling and during bleeding, the downhole measurement performed to have pressure temperature profile. By the measurement, the liquid column was identified from 1900 meter depth into bottom hole.

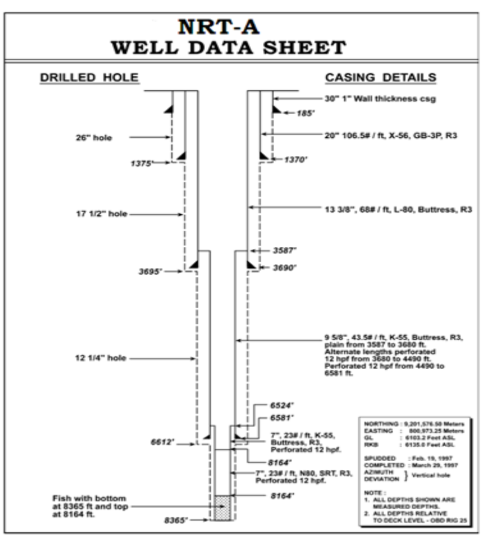

Figure 1: Well configuration of NRT-A.

At the beginning, we divide space up into blocks or elements and time into the sequence of time steps. The grid is generated as radial with input layer into wellbore depth. In the z-direction, it is divided into 425 layers and 23 radial grids in radius 1 km for radial-direction. Notice that the coordinate center (0, 0) for radial grid at TOUGH2 is at the perimeter of the wellbore, not at the center of the radius (*Figure* 2). The grid generation is provided by TOUGH2 through MESHMaker module and offered to define flow system geometry.

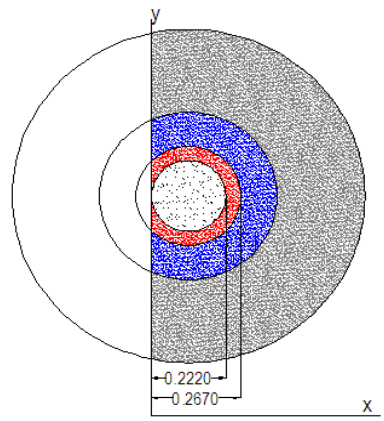

Figure 2: Radial grid generation in the radial direction.

The data needed to characterize the flow system include geologic parameters and constitutive relations of permeable medium (absolute and relative permeability, porosity, capillary pressure, etc), initial and boundary conditions, sinks and sources, and thermophysical properties of fluid.

TOUGH2 execute the simulation by applying the modules inputs or data records, i.e. ROCKS, ELEME, CONNE, INCON, GENER, etc. The last record is ENDCY or ENDFI if there is no flow simulation assigned. ENDFI is used for MESHMaker module in which it does not function to execute the flow simulation but only for create grid generation. Data records beyond ENDCY or ENDFI will be ignored by TOUGH2.

ROCKS module is applied for reservoir domain. In this module, we input parameters of permeability, porosity, heat capacity, thermal conductivity, capillary pressure, and fluid saturation of the reservoir. It can be assigned for several condition of reservoir domain. In this study, we use minimal five types of rocks, specified for wellbore, casing and cement, formation, permeable reservoir, and impermeable reservoir. For other simulation case, we add types of rocks in the need of having a good agreement between simulated and measured pressure temperature profile. The wellbore, assigned as PIPES, is located at the center of radial grid.

Volume elements or ELEME module or is usually put together before CONNE (connections). If ELEME module is present, it must precede CONNE module. At the execution, TOUGH2 always refer to the connection. However, if there is any blocks at ELEME module which is omitted by user, TOUGH2 will ignore the flow simulation for connection at the blocks which are not assigned. There are numbers of elements which we set up as inactive cells. They are replaced by boundary cells as assigned with an extensive volume (V = 10^{20} m^3). It is implemented by assigning to the elements adjacent the boundary so that their thermodynamic conditions do not change at all by the exchange of fluid and heat in the flow domain.

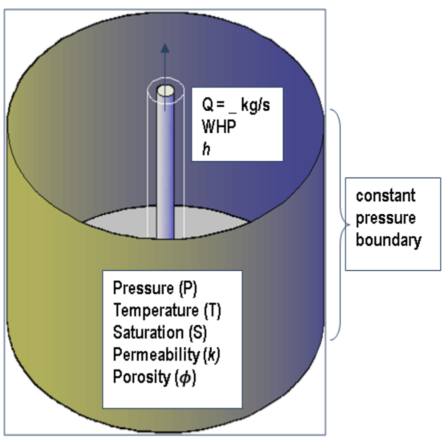

Figure 3: Reservoir domain.

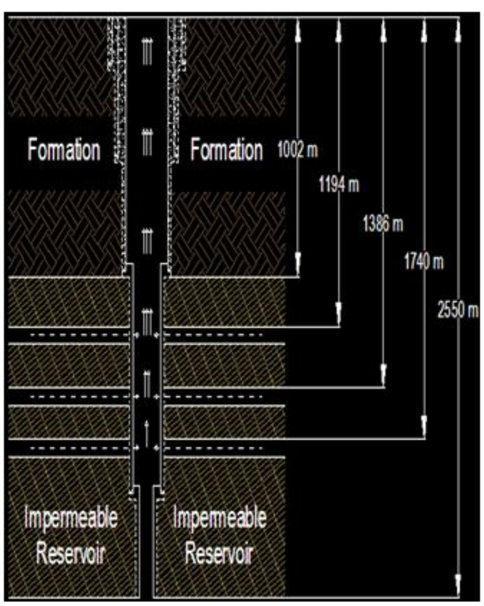

Figure 4: Schematic of Simplified 2D Model.

The pressure temperature and saturation condition are created in INCON module. For two-phase elements condition, we use pressure and saturation at initial condition, and pressure and temperature for single-phase elements condition. Defining that reservoir is occupied by single-phase vapor, the pressure temperature of reservoir at initial condition is considered to have the gradient pressure as vapor-static. The assumption is quite reasonable provided that static pressure measurements are obtained. While for elements assigned as formation, the pressure temperature follows the hydrostatic gradient. The initial condition of casing is similar to that in formation. Different from previous types of rock, pressure and saturation profile is only applied for wellbore since it may occur two-phase flow.

THE SIMULATION EXECUTION

The simulation procedure computes the pressure and temperature at block centers while fluxes (mass and energy) are calculated at block boundaries. By this understanding, we provide an input impulse to gather information of the wellbore/reservoir response. The input may be assigned as wellhead pressure, mass flow rate withdrawn from the wellbore or water injection to the wellbore. Then by matching the model response to the measured reservoir response we infer that the model parameters take the same values of the reservoir parameters.

The simulation was started with the grid generation, consists of layer and radial grid, offered in MESHMaker module. The next step was to define types of rock in which reservoir responds to the governing properties, i.e. permeability, porosity, saturation, diffusivity, etc. First initial condition was assigned from our determination of initial coupled wellbore/reservoir condition, in this case we use vapor-static gradient for reservoir. We apply our first hypothesis, liquid column may be caused by condensation process, by implementing the wellbore initial condition without liquid column occurrence at all. The next step was to simulate bleed-off condition of well with wellhead pressure of 33-33.9 bar for 30 days, 60 days, 90 days,120 days.

By matching the result from simulation with measured pressure and temperature, we may infer whether our hypothesis is representative or not with the real condition in the wellbore. If there is a good agreement between both measured and simulated then we can interpret that the liquid column is caused by condensation process. If else, we should move forward to the second hypothesis by having a statement that the condensation process is not proven yet to cause liquid column with height of 600 meter.

RESULT AND ANALYSIS

Characteristics of Pressure Temperature Profile in Vapor-dominated Geothermal Reservoir

Pressure profile surveyed by downhole measurement in vapor-dominated reservoir is characterized by the steep gradient as it is classified into vapor-static gradient with the temperature profile is above the saturation degree, specify the phase of fluid to be in high temperature vapor, most cases in superheated vapor (so-called dry steam).

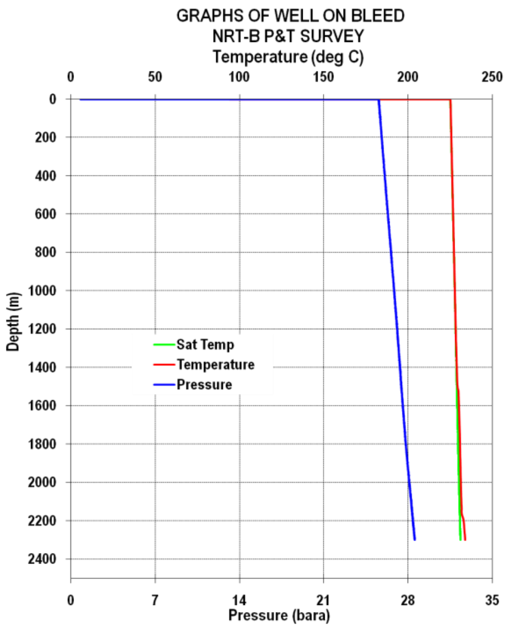

Figure 5: NRT-B PT profile in 2009.

There are two common types of pressure temperature profiles in our area of study. NRT-B, the adjacent well to NRT-A, shows the indication that the well was drilled into the vapor zone only. NRT-B was completed at 2450 meter measured depth, directional well in deviation 15.40°. At the early stage, well testing was performed to obtain initial estimation of productive major feed zones, pressure, and temperature profile, etc. By the PT measurement in 1997, the liquid column was encountered with height of ±150 meter. In 1998, the remaining liquid column was measured with height of ±100 meter. The last appearance of liquid column with height no higher than 10 meter was identified in 2001. In 2009, no liquid column remained inside NRT-B, as displayed in *Figure 5*. Note that, not all wells in our area of study show the same characteristic as NRT-B. Some wells do not show any indication of liquid column at the bottom hole in the initial year.

No wells to date have been drilled to reach the bottom of reservoir. One of the deepest well is NRT-C, which was drilled to encounter zone of boiling water. This can be indicated by the pressure temperature profile as depicted in *Figure* 6. Notice that there is a slope at ±2500 meter depth implying that the transition occurs from vapor zone to water boiling zone. This is a reliable indicator because the temperature profile also follows the gradient of saturation temperature indicating the very high temperature of geothermal fluid. Despite the bottom of reservoir still could extend any farther, the interpretation of the liquid reservoir occurrence beneath vapor reservoir with higher temperature could be drawn with certainty. This information should be incorporated into the conceptual model for having a better reservoir delineation. By downhole measurement in NRT-B and NRT-C, we can *Figure* out the common characteristics of PT profile measured in vapor-dominated reservoir.

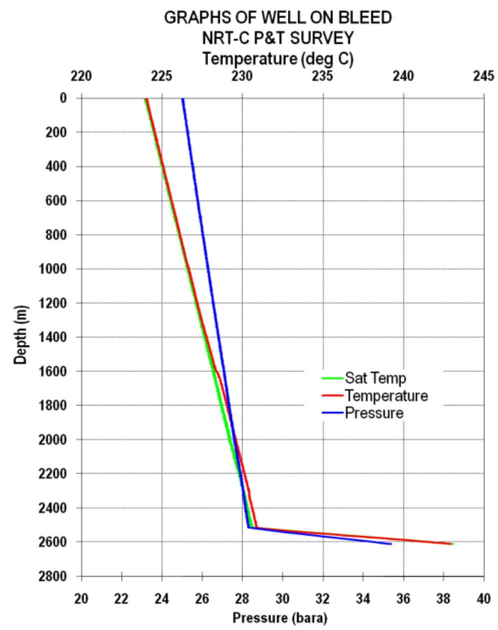

Figure 6: NRT-C PT profile in 2009.

The Anomaly of NRT-A

Anomaly of PT profile occurs in NRT-A, in which liquid column with height of 600 meter has been identified by PT downhole measurements conducted since the initial year 1997 until 2009, when well is set on bleed condition. The anomaly was not completely understood because it does not likely represent the characteristic of water boiling zone. As shown in *Figure* 7, the pressure profile displays a slope started at ±2000 meter down to the bottom hole, indicating the hydrostatic pressure while the temperature gradient appears to be lower than the saturation temperature gradient. Although the pressure gradient shows the hydrostatic gradient from ±2000 meter, the temperature profile at the depth remains stable as compressed liquid without any indication of boiling water.

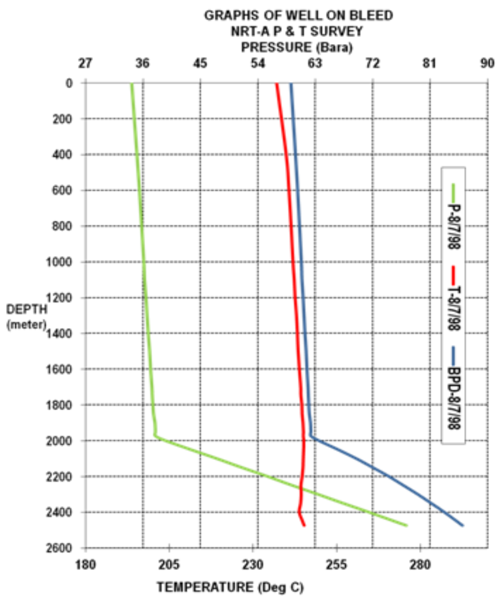

Figure 7: NRT-A PT profile in 1998.

PT Spinner provides data of the permeable feedzones as shown in *Table 1*.

Table 1: PT Spinner Data of Identified Feedzones

No	Depth Interval, m	Top FZ, m	Bottom FZ, m	P @depth, bara	T @depth, bara
1	1197	1197		34.14	242.9
2	1316-1464	1316	1464	34.48	243.5
3	1739	1739		35.10	244.6

No	Depth Interval, m	h, kJ/kg	ρ, kg/m^3	P reservoir, bara	kh, Dm
1	1197	2809.5	17.09	34.14	40.74
2	1316-1464	2809.6	17.26	34.48	102.96
3	1739	2809.8	17.58	35.10	46.20

According to the PT Spinner, we have three major feedzones, with the deepest zone is located in 1739 meter.

Testing 1st Hypothesis: Condensation Process

In testing our hypotheses, we use the same assumptions of initial pressure and temperature of reservoir and formation as we input in analytical study.

We have simulated the well on bleed condition for 120 days. For the first 60 days, major fraction of vapor from the deepest feedzone went up ascending the well while the minor fraction went down to the bottomhole. For the next 60 days, some fraction of vapor at near wellhead likely changes into liquid phase and went down but being detained by other major fluid flow ascending the well so that the liquid phase was never able to reach down the bottomhole.

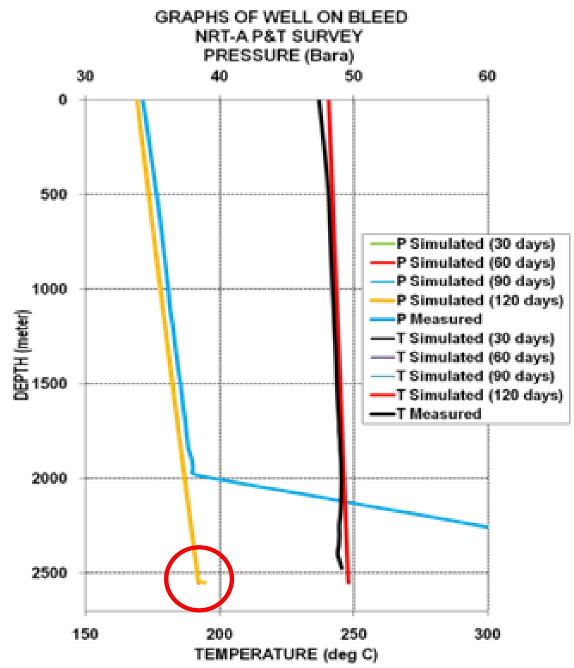

Figure 8: Composite graphs of testing 1st hypothesis.

As shown in *Figure* 8, the liquid occurrence can be encountered after 120-day heating up with height of only 6 meter. The origin of the liquid is from little fraction of vapor from the deepest feedzone which go down into the bottom hole, get accumulated, and not being able to go anywhere due to highly tight surrounding reservoir. The heat transfer in there is driven by conduction from surrounding reservoir and well casing without any massive involvement from convection that can cause the vapor to change into liquid phase because of lower temperature in the surrounding well casing.

The warm-up or heating-up in the real well usually takes only several days, weeks, or a month for the latest. In addition to that, the liquid column inside

NRT-A was identified only a day after the well being completed. If it was associated with the condensation process, it would not have taken only a day to cause 600 meter of liquid column when well was on bleed condition. Therefore, by the simulation we performed and the comparison with data, we may infer that the liquid column is not associated with the condensation process inside NRT-A.

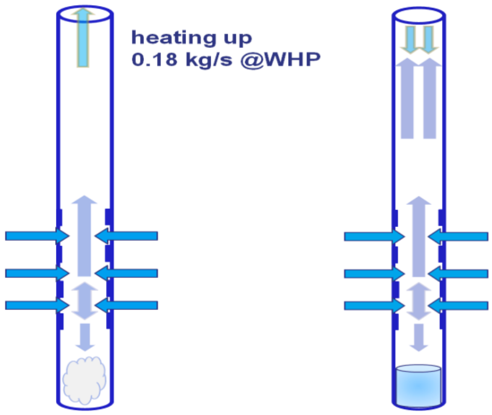

Figure 9: The model of fluid flow in testing 1st hypothesis (left:60 days; right:120 days; generation rate: 0.18 kg/s; WHP : 33.95 bar).

Testing 2nd Hypothesis: Drilling Mud

In the process of testing our 2nd hypothesis, we faced the problem of matching data and simulation result. The difficulty was that we were unable to get the agreement between simulated and measured pressure profile. Although by measuring the pressure gradient to depth, both simulated and measured pressure shows a fair value.

Before simulating the heating up, we simulated the water injection into NRT-A in 20 days duration of injection time. Instead of simulating the water injection during drilling activity, we simulated the injection water into the well when it has already been completed. This is acceptable since we do not concern about how to simulate the water injection during drilling, but about what may occur to liquid column inside NRT-A if we simulate well in heating up and production condition. The results we obtained from water injection simulation were used to determine the initial condition for the next sequence, the well heating up and production.

Figure 10 shows that the height of liquid column simulated is pretty significant higher than the measured column in the real system. Thus, it leads us to a prognosis that the liquid column height may be controlled by permeable feedzone considering that the starting point of the column is located at the deepest major feedzone which can be detected by PT Spinner logging tool.

As shown in *Figure* 10, there is no good agreement between simulated and measured pressure profile. The simulated pressure profile takes higher value than measured pressure at the same depth. We made a presumption that this may occur because there is another feedzone at deeper depth than the deepest feedzone recorded, that could not be detected by PT Spinner survey. The simulated temperature shows an indication of unstable state of compressed liquid due to heating up process in the liquid column was only influenced by conductive zone, i.e. casing and impermeable rock.

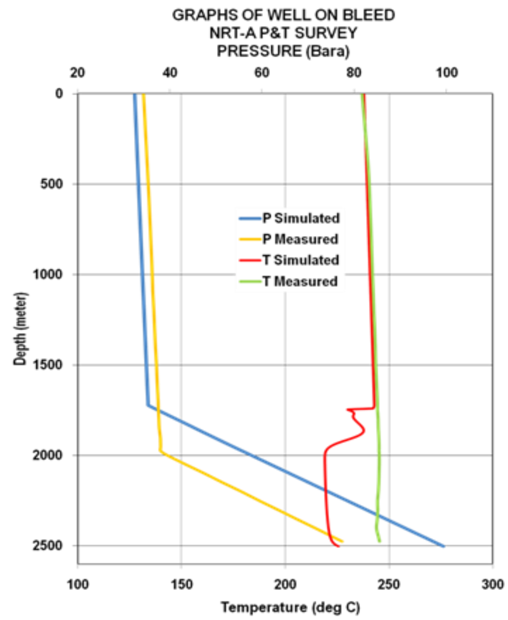

Figure 10: Composite graphs of PT profile (7-day heating up).

In the purpose of having an understanding by which the liquid column temperature is controlled, we performed the simulation by enlarging the value of permeability. As shown in *Figure* 11, the temperature of liquid column was quickly stabilizing at 7-day heating up.

It may not be common to put the value of permeability with 1E-11 m^2 for geothermal reservoir. Note that we only use the number to do the simulation for our model, not to represent the real condition. This was performed to study the response of liquid column temperature by the change of permeability value. The permeability is an important parameter because it controls the well's productivity (as stated in Darcy's equation). If we compare to the result shown in *Figure* 10, the value of permeability has significant influence on heating up the liquid column.

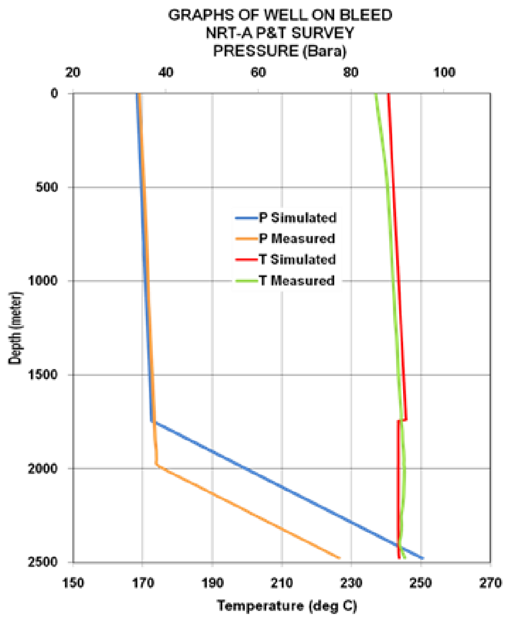

Figure 11: Composite graphs of PT profile (7-day heating up; kx = ky = 1E-11 m^2).

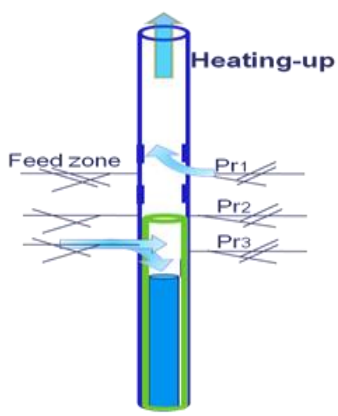

Figure 12: The impact of heating-up on liquid column (Pr = Reservoir Pressure).

Other effort made to decrease the pressure of liquid column was by simulating the permeability of impermeable/tight reservoir with 1E-12 m^2 (previous permeability was 5E-18 m^2) in the z-direction. It was expected that the liquid which was injected may fill the volume of tight reservoir so that it can be dispersed into the larger volume in the reservoir. However, it still did not give any satisfying results.

Thus, instead of adding minor feedzones with permeability 10 mD which may take effect later at production state, we preferred to add one feedzone, with the same value of permeability (1E-12 m^2), beneath the third feedzones, assuming the fourth feedzone could not be detected by PTS survey.

As shown in *Figure* 13, the simulated temperature seems to reach steady state sooner than the measured temperature. This is reasonable considering that we did not simulate the quenching state of the wellbore so that the temperature reaches steady state faster than the measured profile. This also may be caused by our value of permeability which is higher than the real permeability of feedzones in NRT-A as we explained in previous simulation.

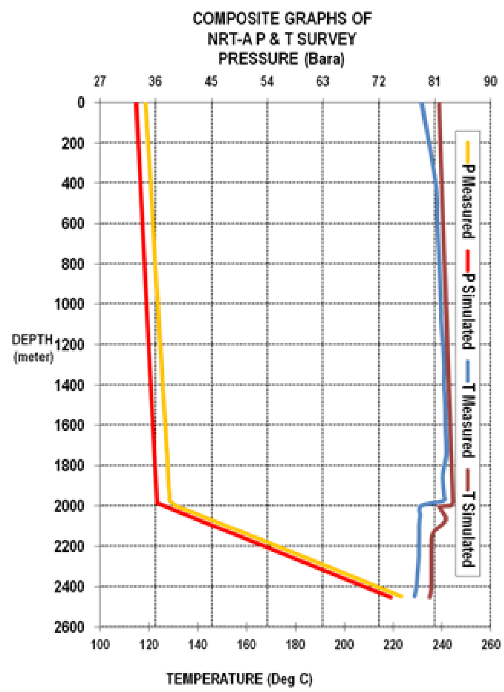

Figure 13: Composite graph of PT profile (7-day heating up after injection of simulated profile; 30-day heating-up of measured profile)

In our simulation, the contribution of the last feedzone which was not detected by PTS was 0.3 kg/s while the total mass flow rate at the wellhead was 15 kg/s at WHP 20 bar. Compared to the total mass flow rate, the contribution from the last feedzone was very small. However when well was set on bleed-off condition, the contribution of the last feedzone was smaller than 0.3 kg/s but it was still effective to vaporize liquid column during bleed-off condition. The simulation may solve the NRT-B behavior. Through our simulation to NRT-A, we presumed the similar process may occur inside NRT-B. The difference is that there is another feedzone at near bottomhole inside NRT-B which contributes steam rate to vaporize the liquid column until there is nothing remained inside NRT-B, although it may take years to vaporize the entire liquid column.

As shown in *Figure 14*, there is a good agreement between measured and calculated PT if we compare them with measured profile at bleed-off condition after production. However, it is reasonable if the temperature of liquid column that we simulated has not yet to reach its steady state because we did heating-up simulation only for 7-days.

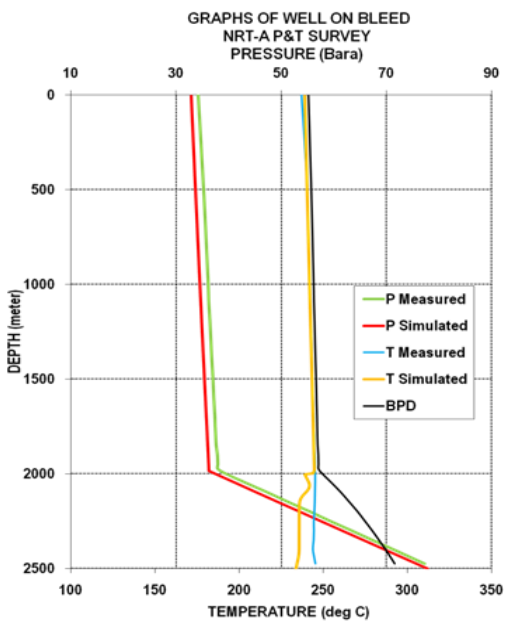

Figure 14: Composite Graph of PT Profile (7-day heating up of simulated profile; Heating-up after production profile of measured PT).

Our previous prognosis about the existence of the fourth feedzone is likely acceptable since we could obtain pressure temperature profile from initial shut-in/bleeding condition that may prove our prognosis with certain.

After well completed, we usually run the PT Spinner tools to have an information about permeable feedzones location inside wellbore. Although it should be integrated with the fluid velocity profile, the PT profile can be used to interpret any location of feedzones as shown in *Figure 15*. From PT profile we may interpret that the first feedzone is located at -+1100 m, +1300 m, +1700 m, and +2000 m. The last feedzone, i.e., at +2000 meter depth may not be detected by PT Spinner because it may produce minor mass flow rate. Note that PT Spinner may not be able to detect minor permeable feedzones with certain value of permeability or minimum mass flow rate.

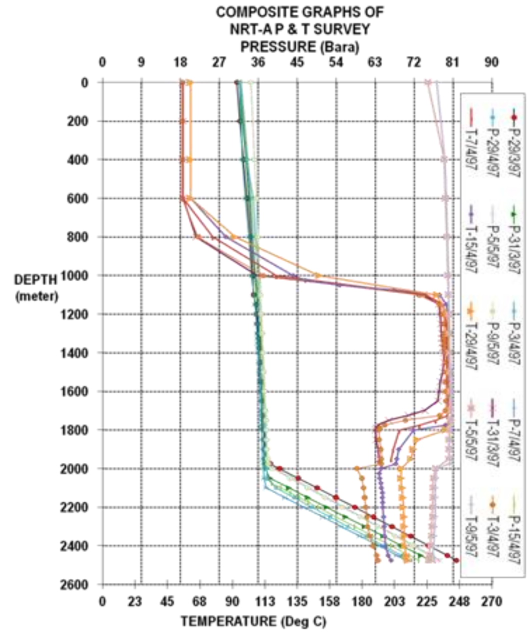

Figure 15: Composite Graph of Initial Shut-in/Bleeding Condition After Well Completed

After matching process finished, we did the next simulation, production testing. The simulation of well production was performed to confirm whether the liquid column would be vanished or not by the production. PT profile of NRT-A taken annually at well on bleed shows the liquid column still exists after being produced as shown in *Figure* 16.

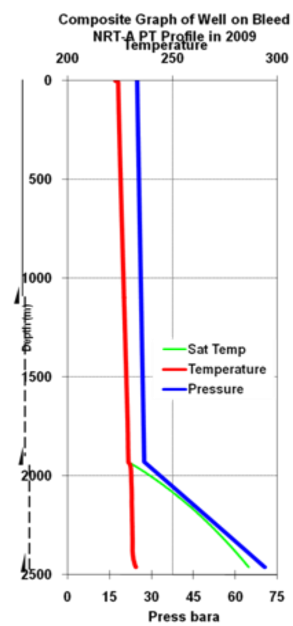

Figure 16: Composite Graph of NRT-A PT Profile in 2009 (well on bleed)

By simulating well on production, we can gather information that the liquid column is still able to be identified which gives us a certain presumption that the liquid column which was present until 2009, is the same liquid column in 1997 which is trapped in the highly tight surrounding reservoir without any permeable feedzone being able to heat up the liquid column.

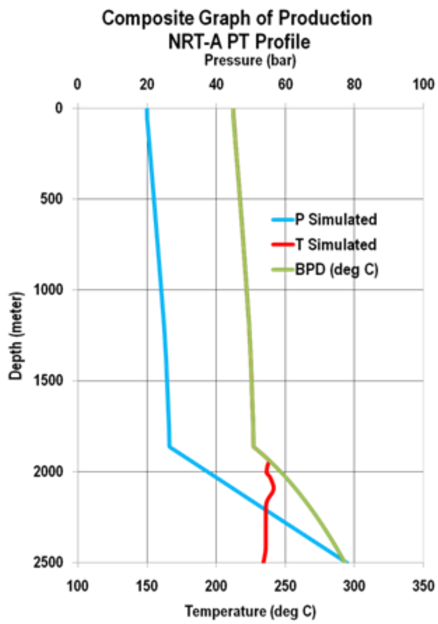

Figure 17: Composite Graph of PT Profile (well production)

The Behavior of NRT-B

The adjacent well of NRT-A, NRT-B, showed the same behavior in the early years. In 1997-2001, the liquid column with maximum height 200 meter was able to be identified inside NRT-B. During the years the liquid column height was decreasing until in 2001 the last appearance of liquid column was observed.

As shown in *Figure 18*, from the PT profile after injection in 1997, we may interpret that there are feedzones at ±1300 m, ±1450 m, ±1900 m, ±2100 m, and ±2400 m. When we combined our interpretation with the data from PT Spinner, it was mentioned that there are more feedzones which are located at ±2000 m but no indication of the last feedzone located at ±2400 meter, as we previously interpreted from PT profile. In other words, PT Spinner survey was unable to identify the last feedzone at 2400 meter, although it is implied in PT profile taken in 1997 that there was an increasing temperature at 2300-2400 meter depth.

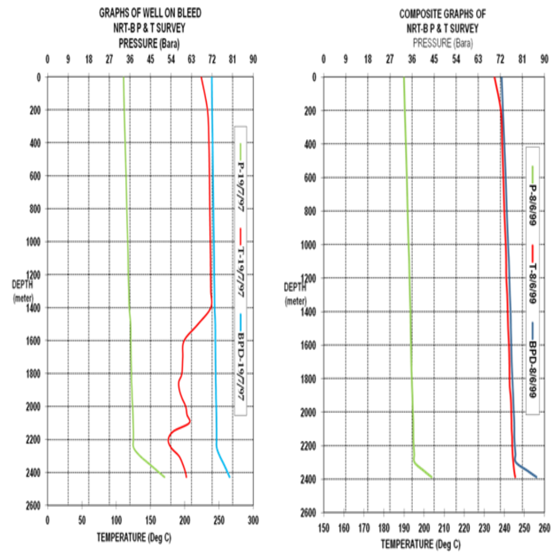

Figure 18: The PT Profile of NRT-B (well on bleed) in 1997 (left) and 1999 (right)

From the PT profile of NRT-B, we may infer that there is fracture-network at near bottom hole that can control liquid column. However, the permeability is considered to be low so that the evaporation of liquid column took years. As previously mentioned earlier, the permeability and location of feedzones give impact on the occurrence of liquid column inside the wellbore.

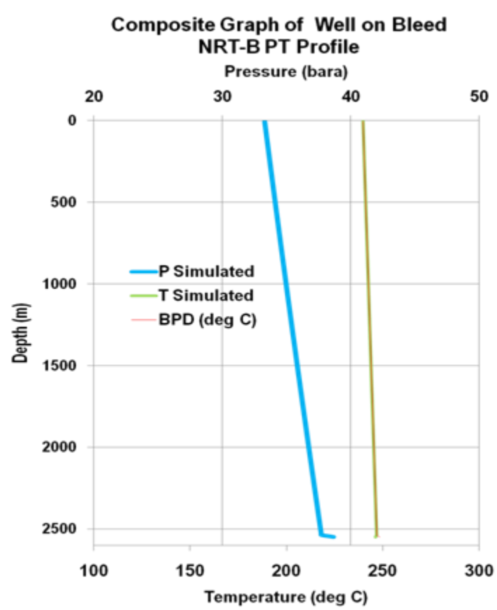

Figure 19: PT Profile Simulated of NRT-B (11-day heating up)

Using the same model as NRT-A, we added more feed zone at near bottom hole to study the response of liquid column to the convection heat transfer by vapor from feedzone. Note, that we did not build model of NRT-B, but we use NRT-A as a model for NRT-B with one feed zone added at near bottom hole. This was simulated to study the contribution of convective heat transfer from hot fluid to evaporate injected water.

As depicted in *Figure 19*, the liquid column was quickly evaporated for 11-day heating up. The result may not represent the real condition of NRT-B since we added major permeability 1E-12 m^2 at near bottom hole, but this may give us a better understanding for the similar phenomenon occurs in other vapor-dominated geothermal reservoir.

Sensitivity Analysis

The sensitivity analysis was performed to notice whether grid dimension can have impact on the results. For that purpose, we built three different grid radial, i.e. 1 km, 2 km, and 3 km. We did the same sequence works for the three different grid model. We started from injection simulation and then we did heating up simulation. The results were satisfying because our grid dimension does not have any significant impact on the distribution of pressure temperature inside wellbore. In other words, our determination about reservoir radius may vary because it does not impact on the pressure temperature distribution inside wellbore since we set boundary in constan pressure temperature.

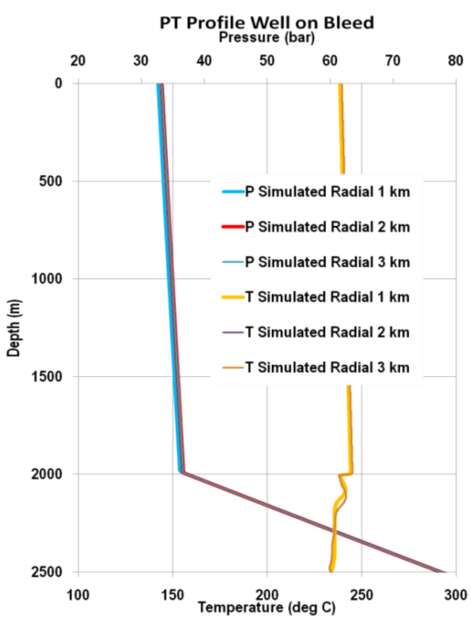

Figure 20: Sensitivity Analysis for Different Radial Grid Dimension.

Similar Cases in Other Vapor-dominated Geothermal Reservoirs

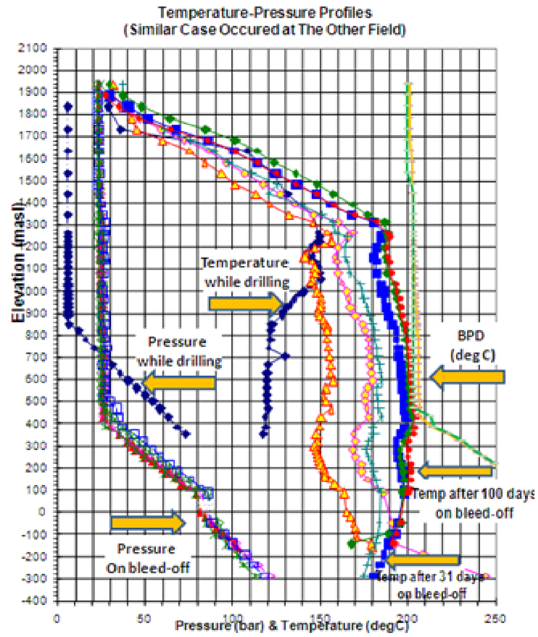

Figure 21: Case example (Higher Liquid Column)

The presence of liquid column were also reported in other vapor-dominated geothermal reservoirs. Similar to our area of study, the presence of liquid column was detected after drilling activity. As depicted in *Figure 21*, 700 meter liquid column is present inside well. Using PT graph we may infer that the last feed zone is located at the top of liquid column. Our previous explanation has stated earlier that the feedzone can control the height of liquid column inside wellbore.

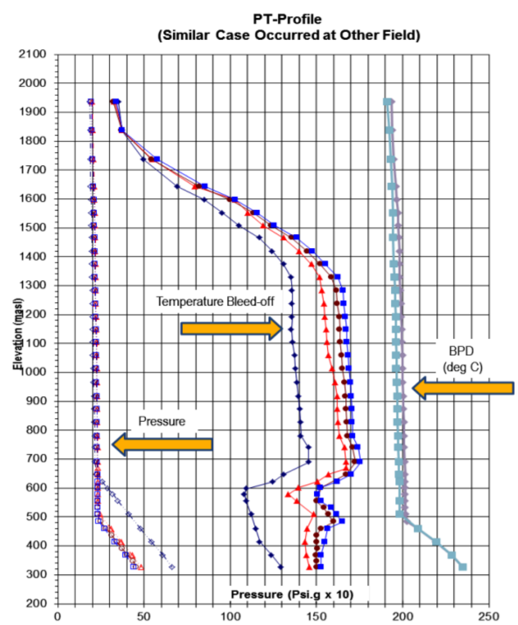

Figure 22: Case example (Lower Liquid Column)

Figure 22, we may infer that the last feedzone is located at +500 m.a.s.l. We can see from the temperature profile that there is temprature raising at +500 m.a.s.l, indicating an active feedzone at the depth. While, the surrounding reservoir beneath 500 m.a.s.l is of very tight permeability which is impossible for fluid to flow in or out to the reservoir.

CONCLUSION

Some hypotheses were proposed to explain the mechanism of liquid column occurrence inside wellbore in vapor-dominated reservoir. The phenomenon is uncommon due to the temperature of liquid column at the borehole was identified as compressed liquid. The hypotheses include condensation process, drilling mud which was trapped due to highly tight surrounding reservoir, and the existence of liquid reservoir.

In the process of testing the hypotheses, we did the simulation using computer simulator. Prior to doing the simulation, we built a simple model of analytical study using Microsoft Excel. Homogeneous approach to calculate pressure drop simultaneously was combined with Hasan Kabir method to calculate heat loss. The purpose of analytical study was to predict the distribution of wellbore pressure and temperature in easier way and better understanding. Despite we have limitation for not being able to prove the process governs the liquid column occurrence, we may have convenient parameters value and assumptions that can be used for our numerical study. This includes the pressure temperature reservoir from the assumption we used in the analytical study which has been proven gives us a good prediction about wellbore pressure temperature profile since there is a good agreement between calculated and measured pressure temperature profile.

In numerical study, we computed the mass and heat balance using simulator TOUGH2. The simulator may help us to gather information about heat and mass flow occur in coupled wellbore/reservoir. Furthermore, we are able to analyze the process which can cause liquid column inside wellbore.

Our model is a cylindrical, homogeneous reservoir with a wellbore at the center. Radial flow with a reservoir thickness of 1500 meter was assumed. No account of skin effects. The residual saturations were assumed 0.3 for liquid and 0.05 for steam. Grant correlation was used for relative permeability.

From the study, we may conclude:

- The liquid column was caused by the drilling mud during injection which was trapped due to the highly tight impermeable surrounding reservoir.
- The highly tight impermeable surrounding reservoir is the zone with no fracture network that surrounds the liquid column so that the liquid is not able to flow out to the surrounding. Throughout years, the liquid column has no significance change of height.
- Condensation process is not able to contribute the liquid column inside NRT-A since it takes 120 days to cause six meter height of liquid column by our numerical simulation. In fact, the liquid column of height +600 meter inside NRT-A was identified one day after the well was completed.
- The liquid column with the same height is able to be identified since 1997 to 2009 as it is measured by PT tool during well bleed-off condition.
- The last feedzone of NRT-A may not be detected by PTS survey due to low permeability or minimum mass flow rate, but through our simulation we may infer that there is another feedzone at depth which controls the liquid column height.
- Liquid column inside NRT-B which was encountered in 1997-2001, finally evaporated in 2002, indicating that there is some permeable feedzone with lower permeability which conduct convection heat transfer to liquid column. If there is not any fracture network surrounding the liquid column, then the heat flow in liquid column is controlled only by conduction and minor fraction of vapor from feedzones which moves downward and heat up the liquid column. When the liquid column temperature has reached its steady state, the temperature follows the static temperature of vapor.
- Similar cases are also found in other vapor-dominated reservoirs indicating the similar process occurred.
- The condensation process occurs does not significantly impact the height of liquid column, therefore it does not interfere steam flow rate from feedzone since the liquid column is only present beneath the deepest feedzone.
- Through our simulation, it is expected that the presumptions about condensation process or the contribution from liquid reservoir can be eliminated therefore better

interpretation of subsurface profile can be obtained.

- The liquid column presence inside wellbore give us the information about the heat flow from the feedzone and its capacity to vaporize liquid within the wellbore. The minor flow rate may impact much later than the major flow rate of feedzone to the liquid column presence.

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