A NATURAL STATE MODELLING OF ULUMBU GEOTHERMAL FIELD, EAST NUSA TENGGARA, INDONESIA

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ABSTRACT

Ulumbu Geothermal Field is located in Manggarai District, Flores Island, Indonesia. It is approximately 13 km south-southwest of the city of Ruteng. The geothermal system of this field is a high terrain type. This field is a part of a government program called Flores Geothermal Island aiming to make geothermal energy as the primary energy used for power generation in Flores Island in 2025. Well testing results indicate that this field has a steam cap underlying liquid dominated reservoir with temperatures of 230-240°C. NW-SE faults are the main geothermal conduit of this field, since most surface manifestations, such as hot springs, fumaroles, mud pots, and steaming ground are found along these faults. The objective of this study is to present a natural state model of Ulumbu Geothermal Field based on geological, geophysical, geochemical, and wells data from several published papers. The model was only validated using available temperatures data from three drilled wells because of limited published data. Moreover, the mass and heat flow of the model were also validated with conceptual model to achieve natural state condition. Such condition was achieved by continuous calibration process by adjusting the horizontal and vertical permeability. The final permeabilities of the reservoir are ranged from 25-65 mD. The model indicates that the temperatures, mass flow, and heat flow profiles are well-matched with the actual data, although the room for further improvements is still available. The steam cap underlying liquid dominated reservoir was also successfully modelled, since the simulated well pressure shows a pressure gradient change at about -700 masl. This model is the first natural state model of Ulumbu Geothermal Field and the first geothermal field model in eastern Indonesia that has been established successfully.

1. INTRODUCTION

Ulumbu Geothermal Field (Figure 1) is located in Wewo, Manggarai, Flores Island, Indonesia. It is approximately 13 km south-southwest of the city of Ruteng and it is situated on the flank of Poco Leok stratovolcano at an elevation of about 650 masl. Ulumbu geothermal field was reported to be the most promising prospect on the island of Flores with 100 MWth discharge from this field (Hochestein *et. al.*, 2010). This field is a part of a government program called Flores Geothermal Island as the release of ministerial decree No. 2268 K/30/MEM/2017 on June 19th by the Ministry of Energy and Mineral Resources of Indonesia. The purposes is mainly to raise the electrification ratio on the island by making the geothermal energy as the primary energy used for generating electricity in 2025. This island has huge geothermal potential covering 65% of all prospect in East Nusa Tenggara, or about 902 MW (EBTKE, 2017).

The geothermal system of this field is vapour dominated at the upper part and liquid dominated at the lower part with temperature approximately 230-240°C (Nasution *et. al.* 2016, Grant *et. al.* 1992). The field started its development in 1992 as a cooperation between Indonesia and New Zealand government, where the Indonesian government was responsible for the organization, supervision, and implementation of the site development, while New Zealand's Ministry of Foreign Affairs Development Assistance Division (then the Ministry of External Relations and Trade) provided financial and technical support to the project (Mendive *et. al.*, 2014).

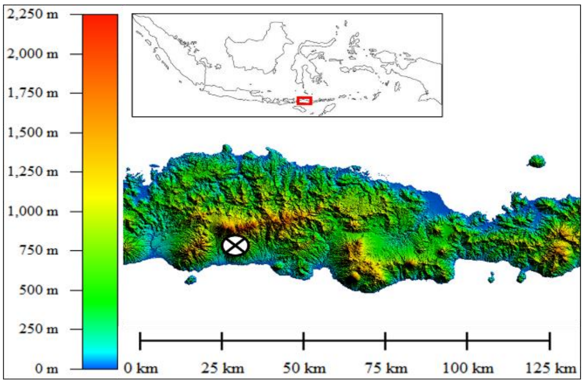

Figure 1: Location of Ulumbu Geothermal Field.

This field is owned by PT. PLN Persero with concession area of ± 10 km^2. Mahon (1992) stated that the preliminary studies in the period of 1969 to 1980's were carried out by Volcanological Survey of Indonesia, PERTAMINA, and PLN. Furthermore, in the period of 1980's to 1992, the feasibility study was done by KRTA Limited. In 1994-1996, the exploration and production drilling studies were held by PT PLN and it was assisted by GENZL and New Zealand government. Three wells had been drilled, a vertical well ULB-01 and two directional wells, ULB-02 and ULB-03. ULB-02 is the only producing well operated generating all 10 MWe electricity, Geological Agency (2004) on Nasution (2016) indicated that this well can generate 10-12 MWe. This field has been through two times of production phase, the first phase has started in November 2011, while the second phase has started in September 2014. Both phases have been generating 2x5 MW, thus the current total capacity of this field is 10 MW (Nasution *et. al.*, 2016)

The objective of this study is to present a numerical model of Ulumbu Geothermal Field which temperature, mass and heat flow profiles, and fluid condition of the model are continuously calibrated using available observation data until the natural state condition was achieved. The natural state modelling was carried out using TOUGH2 (Pruess *et. al.*, 1999). Although modelling process of vapour dominated underlying liquid dominated reservoir is challenging, Ulumbu geothermal field model has established successfully. The model can be used to understand the behavior of the reservoir better as well as to predict the unexplored area of the prospect.

2. CONCEPTUAL MODEL

Conceptual models are a descriptive and qualitative model which provides a whole description of the structure and nature of the system in question. The models are constructed from unified geosciences and wells data and its quality depends on the availability of those data. The data are mainly based on geological information, remote sensing data, results of geophysical surveying, information on chemical and isotopic content of fluid in surface manifestations and reservoir fluid samples collected from wells, information on the temperature and pressure conditions based on the analysis of the available well logging data as well as other reservoir engineering information (Axelsson, 2013).

The following paragraphs are some reviews of geosciences and wells data from several limited published papers of Ulumbu geothermal field.

2.1 Geology

Flores Island is situated on the inner of two concentric ridges which form a part of an active subduction system that extends for about 2,000 km east from Java Island (Utami, 1996). Ulumbu geothermal field is located on the southern flank of Poco Leok volcanic complex and it has an elevation of 650 masl (Mahon *et. al.*, 1992).

Following geological study is based on the work of Setiawan and Suparto (1984). The rocks at this area consist of two ages, quaternary and tertiary volcanic rock. The tertiary volcanic rocks comprising mainly lavas, breccias, tuff, and calcareous sediments act as the basement, meanwhile, the quaternary rocks spread to an elevation of approximately 1,600 masl. The basement rocks are considered to have been down-faulted to the south along an east-west Cancar Fault. The resulting Cancar Depression is assumed to have been partially infilled successively by a massive dacitic tuff from pyroclastic flows and andesite lava flows erupted during the early quaternary volcanism centred north of Ulumbu probably in the vicinity of the Mandasawu Volcanic Ranges. Through time, volcanic activity is believed to have moved further south, where the successive eruption of andesite lava and breccias formed the large Rii strato volcano which eventually collapsed to form Rii Caldera. Renewed volcanism near the centre of the caldera produced andesite lava and tuff breccia partially infilling the caldera.

Kasbani (1997) asserted that in 1987 the youngest volcanic event happened when Anak Ranakah, about 10 km north-east of Poco Leok, was erupted. The rocks consist of basaltic andesites, silicic andesites, and dacitic domes overlying andesitic Poco-Rii volcanic.

2.2 Geochemistry

Almost all thermal features such as hot springs, fumaroles, mud pots, and steaming ground are situated within the crater and on the western and southwestern of Poco Leok complex with the total area of approximately 28 km^2 (Kasbani, 1997). The manifestations are found at the inner rim structure and at the vicinity of NW-SE faults. This evidence shows that those faults might act as the main fault controlling the geothermal activity in this field.

Sulasdi (1996) stated that the hot springs could be divided into 3 groups based on the water temperatures:

- Near boiling point hot springs found in the river of Waikokor valley at elevation of 630 and 665 m
- Hot springs are located at 1.5 km east of Ulumbu with elevation of 820 m to 920 m and have maximum temperature of 68^{o}C
- Warm springs occur at 5 km west of Ulumbu at elevation of 430 m and have temperature 30-50^{o}C

The characteristics of the discharged water are usually acid sulphate and near neutral sodium bicarbonate sulphate. Those water are formed as a result of the heating of surface water by the steam containing carbon dioxide or hydrogen sulfide occurs within 500 m of the surface (Mahon *et. al.*, 1992). There is no hot sodium chloride water discharged from the local springs (Sulasdi, 1996).

Following geochemistry explanations are based on Mahon (1992). Fumarole gases which mainly contains CO_2 and H_2S have concentration of 2-3% weight with CO_2/H_2S ratio of 20 to 30. There was no evidence proved the presence of magmatic volcanic type gases such as SO_2 or HCl from the discharged steam. Geothermometry of the fumarole gases at Wai Kokor indicates that the fluid is derived from a deep fluid source with temperature probably greater than 250°C and possibly as high as 300°C. However, the exact location of the source is not clear whether it is below the fumaroles or at some distance horizontally around them. The water chemistry suggests that the warm springs in the west are further from the source than those at Kokor or Lungar and together with the steam and gas results, suggest that the major upflow zone is beneath Kokor or towards Lungar. That fact might also indicate that the main outflow zone is located west of Ulumbu geothermal field.

2.3 Geophysics

The geophysical study has been done by carrying out resistivity Schlumberger traversing and vertical electrical soundings. The soundings with a maximum AB/2 spacing of 1,000 to 2,000 metres have been done at this field.

The geophysical study indicates that low resistivity layer sandwiched between an upper shallow layer and higher resistivity basement (Mahon *et. al.*, 1992). Nasution (1996) stated that the MT data which distributed from Ulumbu to Mucu area, inside the Pocoleok Caldera, indicate the presence of low resistivity zones with rocks composed of lava and pyroclastic alteration materials caused by fumaroles. The clay alteration shows smectite, pyrophyllite, alunite, kaolinite, and illite, which are part of clay cap having thickness from 500 to 700 m (Nasution *et. al.*, 2016).

Mahon (1992) also asserted as follows. The low resistivity zone has an area of approximately 50 km^2 and it is indicated to be deeper east of Ulumbu and the deepest part of the low resistivity zone is under the area of thermal activity at the Wai Kokor fumaroles. The boundary is clearly defined to the north and the west, but it is opened to the south and east.

At the deeper section, the higher resistivity zones are present. The resistivity values are from 10-50 ohm-m, such high resistivity indicates the presence of reservoir layer having thickness of 800 m to more than 1,500 m (Nasution *et. al.*, 2016).

2.4 Wells Data

In the period of 1994-1996 three wells were drilled at the same well pad. Those wells are located less than 100 m south of fumaroles (Nasution *et. al.*, 2016). ULB-01 and ULB-02 were planned to be production wells while ULB-03 was planned to be a reinjection well. ULB-01 well is a vertical well with total a depth of 1,887 m. ULB-02 well, 4.5 m northeast of ULB-01 well, was drilled vertically to a depth of 214 m, where the kickoff point is situated. ULB-02 well was then drilled directionally to a total measured depth of 878.6 m with a 45º angle of inclination and direction of N52E (Utami, 1996). The reinjection well, ULB-03 well, was also drilled directionally in south eastern direction to a total measured depth of 951 m.

The lithological and permeability zones review below is based on Utami (1996). Two units of rock were penetrated by ULB-01, i.e., volcanic rock unit to a depth of 815 m which divided further into two sub-units and a bioclastic limestone and volcaniclastic rock unit from 815 m to 1,887 m. The upper sub-unit of volcanic rock has thickness of approximately 665 m and composed of volcanic breccia with thin intercalations of andesite lava and tuffs. The lower sub-unit of volcanic rock has thickness of approximately 150 m with thinner intercalations. The lowest unit, the bioclastic limestone and volcaniclastic sediment unit is approximately 1,072 m thick and consists of particularly bioclastic limestone with intercalations of volcanic sandstone, siltstone, basaltic lavas, and tuff.

Good permeability rocks in well ULB-01 are shown by the presence of certain minerals such as quartz, albite, and adularia. Those minerals are present at depths 650-800 m, 900 m, and 1,000 m. The major permeability zones are situated at two depths, i.e. at 680 m where circulation losses occurred and at about 1,800 m where there was evidence showing that the drilling did not result in greater fluid returns than being pumped prior to this depth. On the other hand, lower permeability zones are located at approximately 1,120 m, 1,600 m, and 1,850 m (GENZL, 1994).

Volcanic breccia unit is the only rock unit encountered by ULB-02 well. The upper volcanic breccia rock unit penetrated by ULB-01 well is also present. Good permeability zone of this well is situated at 610 m indicated by the presence of quartz as veinlet filling. There was also total loss of circulation between 626 m and the total depth. Therefore, no cuttings returned along this area. Meanwhile, poor permeability zones were found to a total depth of 680 m as indicated by no loss of circulation encountered.

Ulumbu geothermal project is categorized as a mini project, thus the well testing program to determine the reservoir characteristics was designed as efficient as possible in terms of time and cost. The discharge test was then held after drilling, Grant (1997) asserted that the temperature measurement after discharge test for all wells indicates nearly the same results, meanwhile the pressure profiles show the liquid zone beneath the steam column. The lower section of the three wells is probably a liquid dominated reservoir as the evidence show that there are downflows within the liquid column and also there is liquid discharged from ULB-01.

Figure 2 shows the shut-in temperature profiles for all wells. ULB-01 temperature profile is a result of 30 days of heating, the temperature inversion occurs at depth of 695 m where the temperatures decrease from 230ºC to 206ºC (Utami, 1996). The circulation loss also occurs at this depth. Therefore, it could be assumed that the major permeability zone in this depth might be relatively cold inflow (Sulasdi, 1996). The stable temperature here is approximately 220ºC. It is also interesting to see that temperature inversion at ULB-01 indicating this well is not situated on the upflow zone of the geothermal reservoir, the upflow is presumably located upslope from the existing well (Grant, 1997).

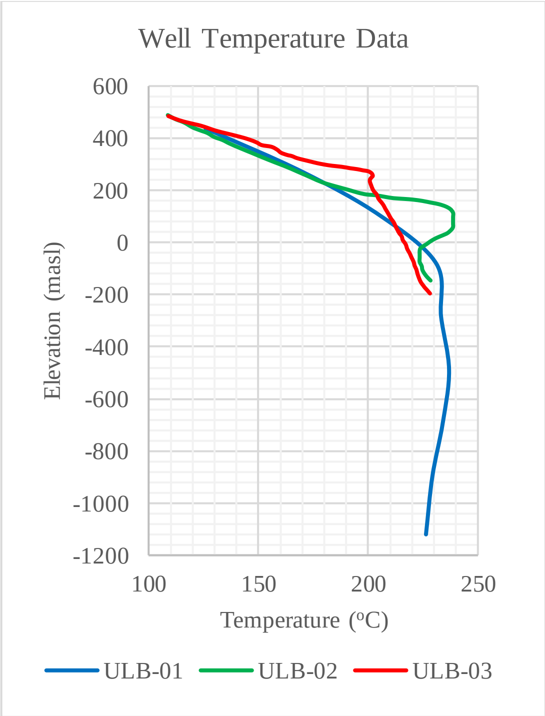

Figure 2: Well shut in temperature profile (After Kasbani., 1997).

ULB-02 temperature profile is a result of 11 days of heating (Kasbani *et. al.*, 1997). At depth of 700 m, the temperature reversal also occurs, the temperature changes from 239ºC to 225ºC and it is associated with total lost of circulation at this zone (Utami, 1996). ULB-03 temperature profile is a result of the longest shut in period compared to other wells, it had been closed for about 7 months (Kasbani, 1997), but did not show any clear indication whether or not there was convective regime in the borehole.

2.5 Compiled Data

All geological, geochemical, and geophysical data are compiled into a conceptual model, Figure 3 shows the conceptual model of the field by using slice plan ENE-E-W. The model consists the components of a geothermal system, starts from heat source, reservoir, cap rock, recharge, and discharge area. Isotemperatures profile and steam cap zone are also shown.

3. COMPUTER MODEL

3.1 Gridding and Layering System

This model is using EOS1 for water and water with tracer because of data limitation and to simplify the modelling process. Figure 4 shows the area planned to be the boundary of the model while Figure 5 shows the plan view of the grid model. Distributed parameter approach is used. The model consists of total 15 layers with top layers follow the topography. The vertical extent of the model is from 2,200 masl to -2,200 masl. The structure direction trend is based on major geothermal conduit which is about 11 degrees from north to west to accommodate the predominant flow direction.

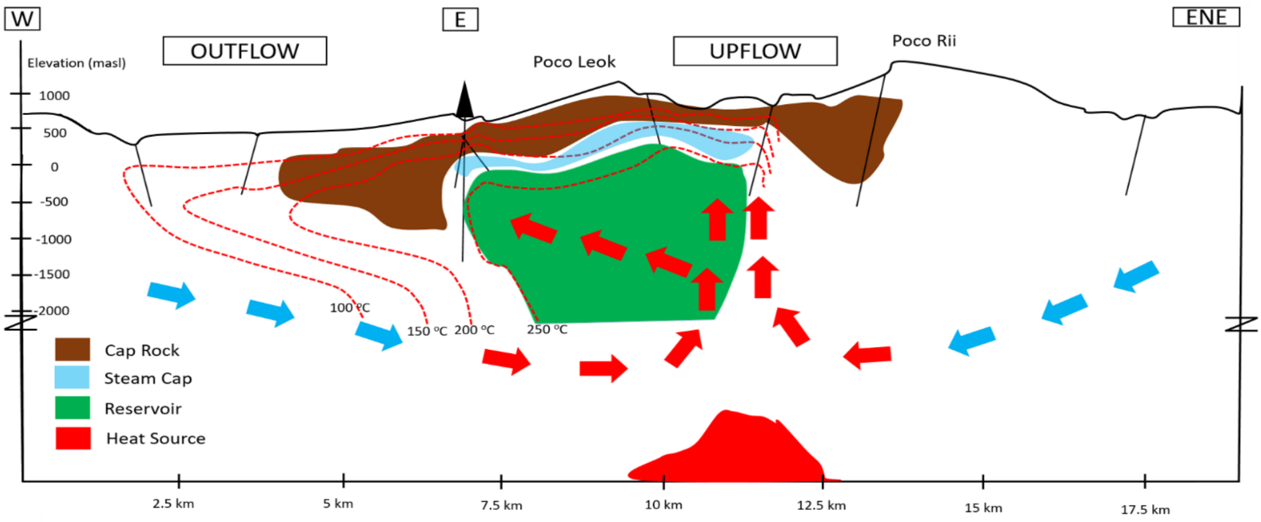

Figure 3: Conceptual model of Ulumbu geothermal field (After PLN, 2016).

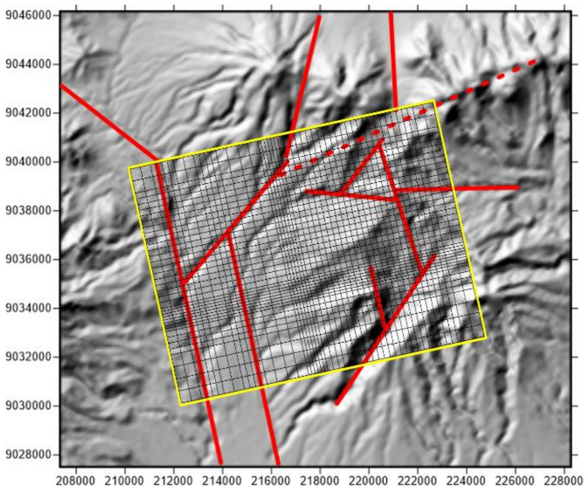

Figure 4: Gridding area is shown in yellow. The red lines are faults.

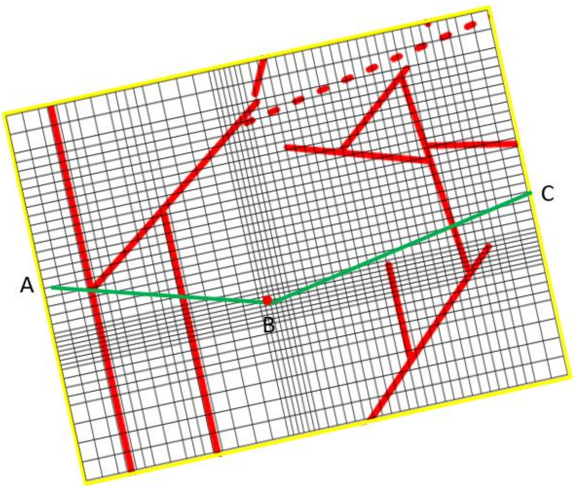

Figure 5: Plan view of grid model with faults are shown in red. All wells are located at the same wellpad pointed out by red dot.

Furthermore, rectangular grid approach is chosen. The size of the grid block depends on the geological condition. The size of the biggest grid is 500 m x 500 m, while the moderate size grid is 250 m x 250 m, and the smallest grid is 125 m x 125 m. Smaller grid blocks are used near the reservoir area, wells, and faults to adequately represent the geological condition and to increase the modelling accuracy on those area. The model consists of total 25,650 grid blocks with total area of 130 km^2 (Figure 6). The model was made large enough to cover upflow, outflow, and recharge zones.

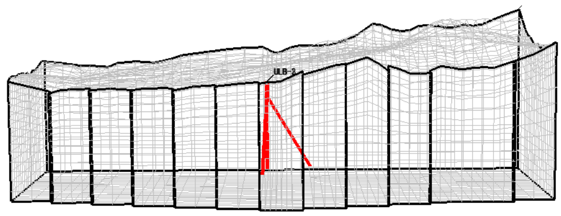

Figure 6: Gridding and layering system of the model on A-B-C.

3.2 Rock Properties

In TOUGH2 simulator (Pruess *et. al.*, 1999), there are several parameters to be assigned to define certain type of material such as specific heat, wet heat conductivity, rock density, porosity, and permeability (x, y, z direction). In natural state modelling, the most important parameter is permeability, because it will control the magnitude and direction of mass and heat flow, and also the distribution of pressure as well as temperature. Because of limited subsurface data, the permeability was acquired from the trial and error attempts, it was continuously adjusted to achieve the best output which corresponds to the available validation data. Table 1 shows the list of calibrated material properties while Figure 7 shows final rock properties distribution in the model based on the interpretation of exploration data and conceptual model.

Table 1: List of rock properties.

Material	k_{xy} (mD)	k_z (mD)	Colour
ATM	1,000	1,000	
GW	0.5	0.5	
CAPR	0.0001	0.0001	
FAULT	100	50	
RES1	65	65	
RES2	60	60	
RES3	50	50	
RES4	40	40	
RES5	25	25	
ROCK1	20	10	
ROCK2	17.5	10	
ROCK3	10	10	
ROCK4	5	5	
ROCK5	0.1	0.1	
ROCK6	0.3	0.3	
HS	100	100	

3.3 Initial and Boundary Condition

3.3.1 Initial condition

Initial conditions are needed to assign pressure and temperature value to each grid blocks in the model at initial state to accelerate the modelling process. In this case, pressure and temperature are dependent on another variable (depth). The normal gradient for both pressure and temperature was used in this initial condition. Two points were used to construct the equation, the first point is at the highest elevation (2,200 masl) having temperature of 25°C and pressure of 1 atm, while the second one is at the lowest elevation (-2,200 masl). Below are equations used for assigning the initial conditions.

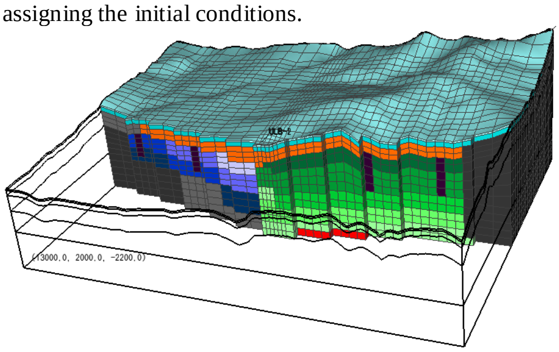

Figure 7: Rock properties distribution on A-B-C.

$$P = 4.02 \times 10^6 - 137.23z \quad (1)$$

$$T = 91 - 0.03z \quad (2)$$

Where: P is pressure (Pascal); T is temperature (°C); z is elevation (masl)

3.2.2 Top boundary and surface injection

The top boundary was set to be at atmospheric condition. It was assigned the fixed value of 1 bar for pressure and 25°C for the temperature. This layer used big volume factor to keep the parameters constant at their initial conditions.

To simulate the cold inflows from the rain infiltration, a surface injection needs to be added. The surface injection was defined by using the annual rainfall data of Flores Island of 2,281 mm/year (BMKG, 2017) with assumed infiltration rate of 10%. Each grid block size has its own recharge mass rate, as indicates in Table 2. All grid sizes used the same injection enthalpy of 104.8 kJ/kg which is the enthalpy of liquid water at 25°C.

Table 2: Recharge rates for each grid block size.

Grid Size (m^2)	Recharge Rate (kg/s)
250,000	1.803
125,000	0.901
62,500	0.451
31,250	0.225
15,625	0.113

3.3.3 Side boundary

The side boundary is assumed to be no-flow boundary and its materials are treated to be impermeable. However, in this case the permeability of the side boundary was not set as impermeable as in one phase vapor reservoir since the reservoir itself is in two phase condition. The permeabilities are ranged from 0.1 to 0.3 mD.

3.3.4 Bottom boundary

The bottom boundaries are the heat source and other rocks treated as relatively impermeable. Because of the limited published data, the heat source final temperature, pressure, and location were acquired from trial and error attempts. The heat source temperature and pressure were set at 311.5°C and 142.5 bar respectively. The location was initially based on conceptual model, but in the end, it needed to be expanded and distributed as the temperature profiles in all wells are not suitable with the actual data. In addition, to keep the heat source pressure and temperature from changing, the volume factor was set at 1.0E+38. Heat flux of 0.08 W/m^2 and hot mass recharge of 0.0025 kg/s/m^2 with enthalpy of 1,411 kJ/kg (liquid water enthalpy at 311.5°C) were assigned into the heat source location. Heat flux and mass recharge rate were also assumed because of no data available.

3.4 Natural State Modelling Result and Analysis

The objective of this natural state simulation is to reproduce the initial temperature and pressure distributions before any exploitation. To achieve such condition the model was run until reached the steady state condition and its simulation time was the same or greater than the geological time. The results of the simulation were compared to the actual temperature data obtained from the shut-in test of ULB-01, ULB-02, and ULB-03 wells to determine the validity of the model. In addition, the mass and heat flow profile, and fluid condition were also checked. To acquire well-matched condition between the model and the actual data, it is necessary to make several adjustments to the model during calibration phase. The commonly adjusted parameters were permeability structure, temperature, and pressure of heat source, and also the location of the heat source. The heat flux and mass recharge remain the same as the initial condition.

Because of published data limitation, there are only temperature data for validating the model. The data were obtained from shut-in test of three exploration wells, they are ULB-01, ULB-02, and ULB-03. Figure 8-10 show the comparison between the model temperature and the real temperature of ULB-01, ULB-02, and ULB-03, the pressure data in the reservoir region resulted from the model are also shown. Figure 8-10 indicate that the temperature from the actual data and the model are well-matched, although there is still room for further improvements. The matching results of ULB-02 and ULB-03 well are not as good as ULB-01 well, but both of them are acceptable since the trends agree with the actual data.

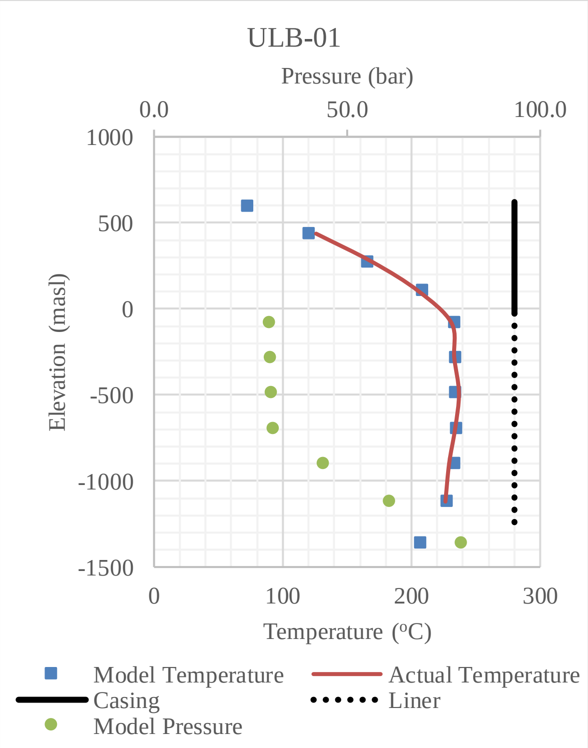

Figure 8: ULB-01 well temperature and pressure profile.

Figure 8 shows both model and observation temperature of ULB-01 well. The maximum model temperature of 235ºC is located at -489 masl and -693 masl. The most interesting feature of the profile is that at -897 masl, the temperature is begun to decrease. Therefore, this proves Grant (1997) report that the well is not situated on the upflow region of this field. High temperature gradient profile shown from the surface to an elevation of -81 masl indicates the heat transfer is dominated by conduction caused by the heat flows through impermeable rock (cap rock). Below that point, the profile indicating the occurrence of convection heat transfer caused by the movement of fluid in the permeable rock. The presence of liquid column asserted by Grant (1997) has also been proven by the gradient change of model pressure at about -693 masl which accompanied by below saturation temperature profile. The pressure gradient change is caused by the change in density of water where the liquid or liquid dominated condition have greater density, so does its hydrostatic pressure, than one phase vapour or vapour dominated condition.

Figure 9 indicates the temperature matching of ULB-02 well, the model shows good correspondence with the actual data, except at -74 masl where the loss circulation occurred. The colder profile at a depth of -74 masl is probably not caused by cold inflow zone, but it was due to insufficient heating considering short shut-in time after drilling. The convective regime of this well is begun at an elevation of 134 masl. The extended temperature profile of this well predicts the characteristics of the reservoir to an elevation of -1,360 masl. The model pressure profile is in similar pattern with ULB-01 well, but at an elevation where the gradient change is happened, the fluid is probably not in liquid condition considering the temperature profile also gives the same ascending trend. Therefore, it is predicted that at depth below pressure gradient change the fluid is likely in one phase vapour or in two phase condition. This condition is reasonable considering the direction of the extension well is relatively closer to heat source than other wells direction.

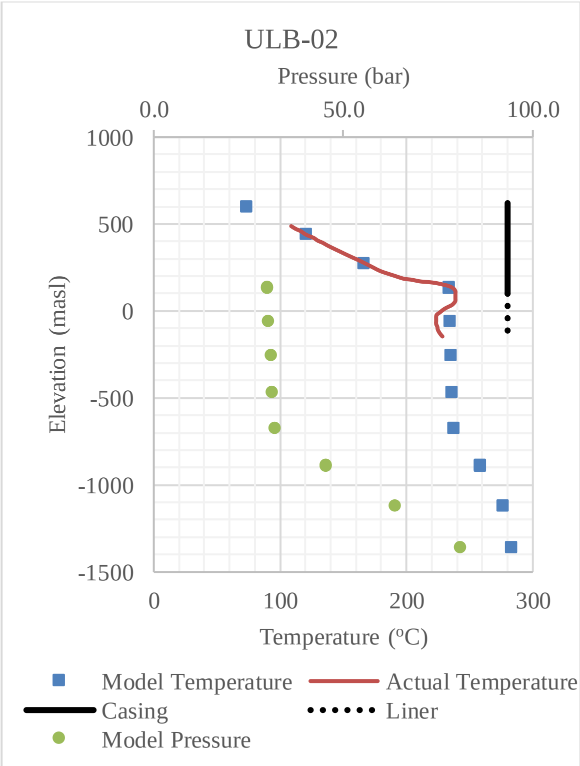

Figure 9: ULB-02 well temperature and pressure profile.

Figure 10 shows relatively matched profile of the model and the observation temperature. The extended temperature profile of this well is nearly the same to the ULB-01 well where there is a liquid column beneath the steam dominated zone, but with shallower depth. The resulted liquid column is relatively colder than at ULB-01 well, this agrees with the relative position of this extension to the heat source. The model temperature profile shows the beginning of convective regime at -70 masl which is slightly not matched with the observation data. The observation temperature profile does not show clearly whether or not there is a convective regime. The profile might be resulted from the rocks having poor permeability penetrated by this well. The matching process of this well was challenging considering all wells were drilled at the same well pad. The calibration process of one well generally affects other well matching condition as well.

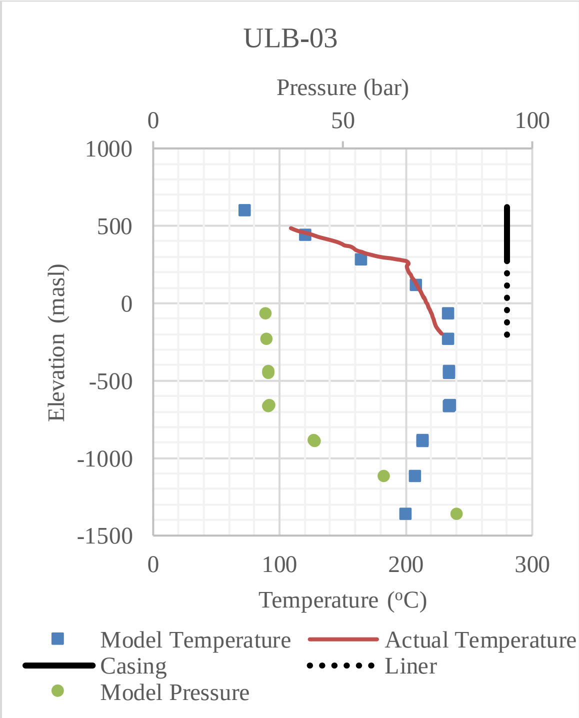

Figure 10: ULB-03 well temperature and pressure profile.

After the temperature data matching was done, the next step was to compare whether the fluid and heat flow profile, and also the fluid condition in the reservoir correspond to the conceptual model (Figure 4). Based on the conceptual model, the upflow of this field is located between Poco Leok and Poco Rii. Meanwhile, the direction of the outflow towards west. There are two recharge areas, the first one is on the west flank towards east, and the second one is from the opposite direction. Because of the convection process occurs in the permeable system both heat and mass flow approximately have the same direction. The fluid flow path is halted when it encounters the impermeable materials such as cap rock and side boundary with very small permeability. Meanwhile, the heat would remain flowing through those impermeable rocks by conductive heat transfer. Figure 11-12 show that the fluid and heat flow of the model are matched to the conceptual model. In addition, the temperature distribution pattern of those figures also successfully reflects the conceptual model.

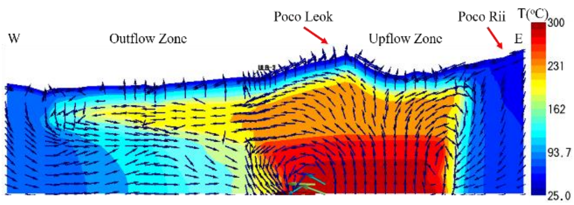

Figure 11: Model heat flow profile.

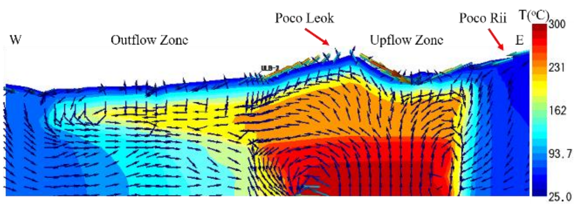

Figure 12: Model mass flow profile.

To analyse the fluid condition in the reservoir, the slice plan showing fluid saturation condition and flow direction for each phase are shown in Figures 13-14. In attempt to reach this fluid condition, reservoir and boundary permeability were adjusted simultaneously. The steam cap formed by enlarging the difference between the reservoir and the boundary permeability, where the reservoir should have greater permeability than the boundary, this condition would allow the fluid to gain sufficient heating thus the steam could be formed. On the other hand, the liquid region formed by doing otherwise, by setting nearly the same permeability between reservoir and boundary. It would allow the exposure of the reservoir to the outside regions supplying enough recharge to the reservoir thus the liquid condition could be maintained.

Figure 13 shows the vapour mass flow path in the reservoir, the boiling zone is probably situated at depth of -1,120 masl where there is the beginning of intensive vapour flow towards the upper part of the reservoir. The vapour dominantly flows towards west of Ulumbu after it reaches the cap rock, and a little amount of vapour is flowing towards east. Vapour saturation values of 0.7-0.8 are prominent in the vapour dominated zone generated from the model, it is appropriate with vapour dominated zone on Pratama (2016). This value is also in the range of vapour dominated reservoir defined by SKM (2008) where the typical volume of water at unexploited vapour dominated zones seems to be around 30%.

Figure 14 indicates the liquid water mass flow direction in the reservoir and its surrounding. At the vapour dominated region, the liquid flows downward starting from the impermeable rocks. This might indicate that this liquid is condensate derived from the condensation of vapour phase. The phenomenon is explained as follows. Vapour phase flowing towards the upper part of the reservoir would be halted by the impermeable rock and flow laterally while the heat is continuously loss through the cap rock. After that, the condensation will occur. The downward movement of the condensate is resulted by the effect of gravity as the density of condensate is naturally higher than the steam. Those processes are suitable with D'Amore and Truesdell model in Grant (1982). From both figures, because of density difference, the movement of liquid water would be in the opposite direction to the steam. Thus, it can be interpreted that the heat transfer process is occurred by counter flow. This heat transfer mode usually becomes the major process transporting a large amount of heat in the vapour dominated area. In this area, the conductive heat transfer is relatively small because of the small vertical gradients of pressure and temperature (Pruess *et. al.*, 1985). At the region surrounding the reservoir, the liquid water seems to flow from both sides of the model into the centre part of the model indicating meteoric water recharge of the geothermal system.

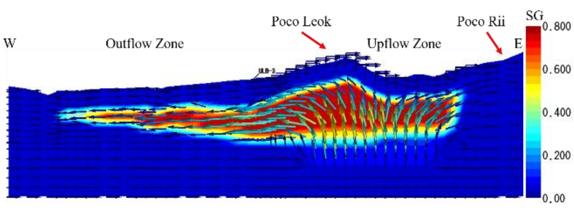

Figure 13: Vapour phase flow.

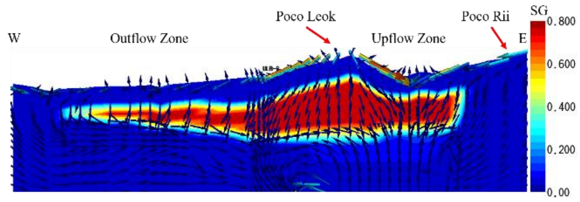

Figure 14: Liquid phase flow.

4. CONCLUSION

The first natural state model of Ulumbu geothermal field has established successfully. All wells temperature data from the model are well-matched with the available shut-in temperature data, although the room for further improvements is still available.

The mass and heat flow profiles are suitable with the conceptual model. By analysing the vectors direction of those profiles, it is concluded that the location of the upflow zone, outflow zone, and recharge area are also matched with conceptual model information.

The reservoir fluid condition of the steam cap underlying liquid reservoir has also successfully modelled, proven by the pressure and temperature profiles of ULB-01 and ULB-03. The boiling zone of this reservoir is probably located at -1120 masl at the area below Poco Leok-Poco Rii. The vapour dominated zone saturation of 0.7-0.8 is also suitable with the references.

This natural state model is also used to predict the condition at the deeper part of the drilled areas. It is predicted that ULB-02 well contains the thickest steam zone than the other wells. ULB-01 and ULB-03 are predicted to contain liquid zone beneath. Therefore, the bottom part of these wells most likely to have lower enthalpy than at ULB-02.

5. RECOMMENDATION

Further works are required to improve the model:

i. Include surface manifestations to the model and validate it by using the actual manifestation temperature and mass flow data
ii. Extend the study to history matching by using production data and perform future scenario simulations

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