Numerical Modeling of the Ogiri Geothermal System, Kyushu, Japan

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Natural-state simulation, history matching, depletion of two-phase geothermal reservoir

ABSTRACT

A three-dimensional numerical reservoir model of the Ogiri geothermal field was developed through natural-state simulation and history matching using the code TOUGH2 (Pruess et al., 1999). The conceptual model of the Ogiri field shows that the geothermal system consists of a two-phase upper reservoir overlying a hot-water reservoir. Therefore, it was necessary to develop a numerical reservoir model that can represent the two region system. The constructed model was characterized by the presence of a high permeable zone that represents the main production zone of Ginyu fault and of the probable recharge zone at depth located in the eastern part of the field. In the natural-state simulation, the observed and calculated temperature profiles and pressures were matched well, confirming the validity of the conceptual model and providing initial conditions for the subsequent history matching simulations. In the exploitation modeling, a good agreement was obtained between simulated and measured temperature and pressure histories. Moreover, the constructed model reproduced the measured enthalpy histories in the 13 production wells reasonably well. Finally, the amounts of steam and internal energy in the geothermal reservoir system were evaluated quantitatively in both the preexploitation and exploitation stages and the causes of the depletion of the Ogiri geothermal reservoir were analyzed based on our modeling study.

1. Introduction

The Ogiri geothermal field has been producing steam and water since 1996. Nittetsu Kagoshima Geothermal Co. (NKGC) has developed the field and supplies steam to a power plant with installed capacity of 30 MWe operated by Kyushu Electric Power Co. At present, the number of production and reinjection wells are 14 and 9, respectively, while they were 10 and 7 when the operation of the plant was started (Japan Geothermal Energy Association, 2000). The steam production rate is approximately 275 t/h and the separated hot water for reinjection is 875 t/h at the separation pressure of 0.24 MPa (Japan Geothermal Energy Association, 2000). The power plant maintains a high utilization efficiency of 96.2% as of December, 2004 (Horikoshi et al., 2005).

Production rate decreased with time after the operation of the geothermal power plant was started. Therefore, a numerical reservoir model needed to be developed to analyze the reservoir behavior after development, to find the causes of depletion and to make forecasts of the future reservoir performance. Geological information of the Ogiri geothermal field shows that the geothermal system consists of a two-phase upper reservoir overlying a hot-water reservoir. The two-phase region is very important because it has an excellent potential to produce a large amount of steam. However, the construction of a numerical reservoir model that can represent the hot-water, two-phase reservoir system and the accurate estimation of the reservoir performance with the numerical model are significant challenges because the reservoir is complex. So far, Kumamoto et al. (2008) reported the development of an earlier numerical reservoir model of the field in its natural state, using the iTOUGH2 numerical simulator (Finsterle, 2000).

In our earlier investigation, we developed a three-dimensional numerical reservoir model of the Ogiri geothermal field and carried out natural-state simulations. The optimum values of rock permeabilities in the Ogiri field were estimated successfully in the study. However, the constructed model could not represent the existence of two-phase conditions within the model in the natural-state condition. The present study describes the updated model that can represent the two-phase conditions and we especially emphasize the natural state simulation and history matching with the model. The natural-state (preexploitation) model was calibrated by matching the temperature profiles of 11 wells and the initial measured pressure at the feed points of the nine wells. About 22 years of production and reinjection data (from 1984 to 2006) were used in history matching and to analyze reservoir performance. In the exploitation modeling, the simulated temperature and pressure histories were compared against the measured values in two observation wells. Furthermore, measured enthalpy histories in the

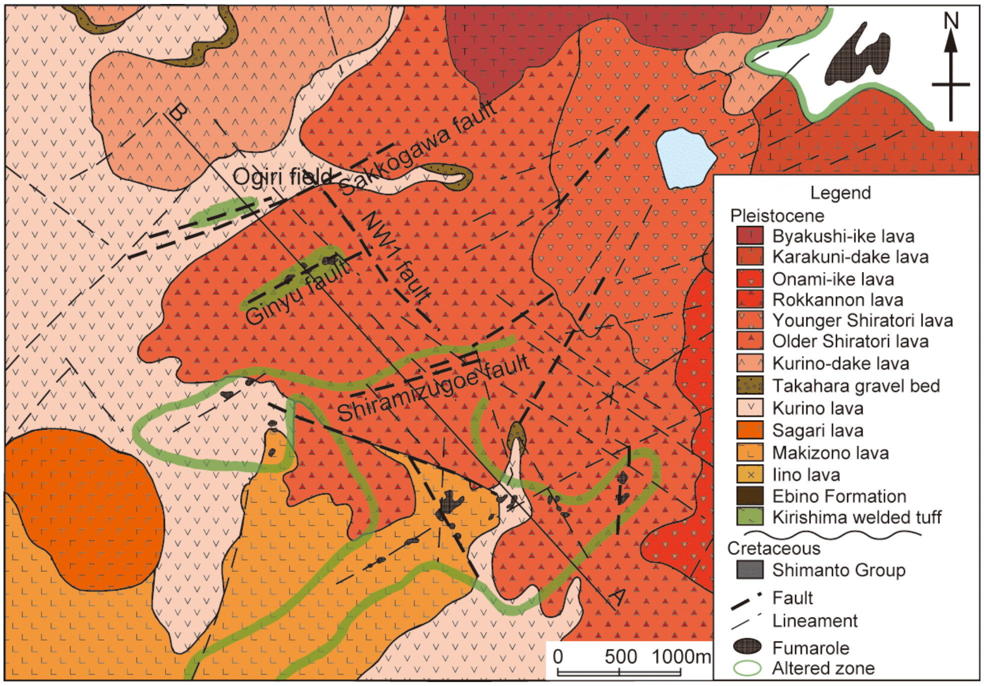

Figure 1. Geological map of the West Kirishima area (modified from Goko (1995, 2000)).

13 production wells were used to compare with simulated values during the history matching.

2. Geological Setting

The Ogiri geothermal field is located in the West Kirishima geothermal area, at an elevation of 700m to 900m above sea level (a.s.l) on the western flank of Kirishima volcano in southern Kyushu. Figures 1 and 2 show the geological map and the geological cross section of the West Kirishima geothermal area. The basement rock is the Cretaceous Shimanto Group consisting mainly of sandstone and shale. Quaternary andesitic lavas and pyroclastic flow deposits with a small amount of lacustrine sediments unconformably overlie the Shimanto Group (NEDO, 1983; 1987; Taguchi et al., 1983; Imura and Kobayashi, 2001). The volcanic rocks consist mainly of pyroxene andesite with minor amounts of hornblende andesite (Goko, 2000). Many hydrothermal alteration zones are found in the West Kirishima geothermal area (Kodama and Nakajima, 1988; Goko, 2000). In general, these zones are aligned along ENE-WSW and NW-SE directions, and they are interlaced. Distribution of alteration zones matches relatively well with the lineament in this area. This characteristic implies that the fracture system at deep zone controls the formation of the alteration zones.

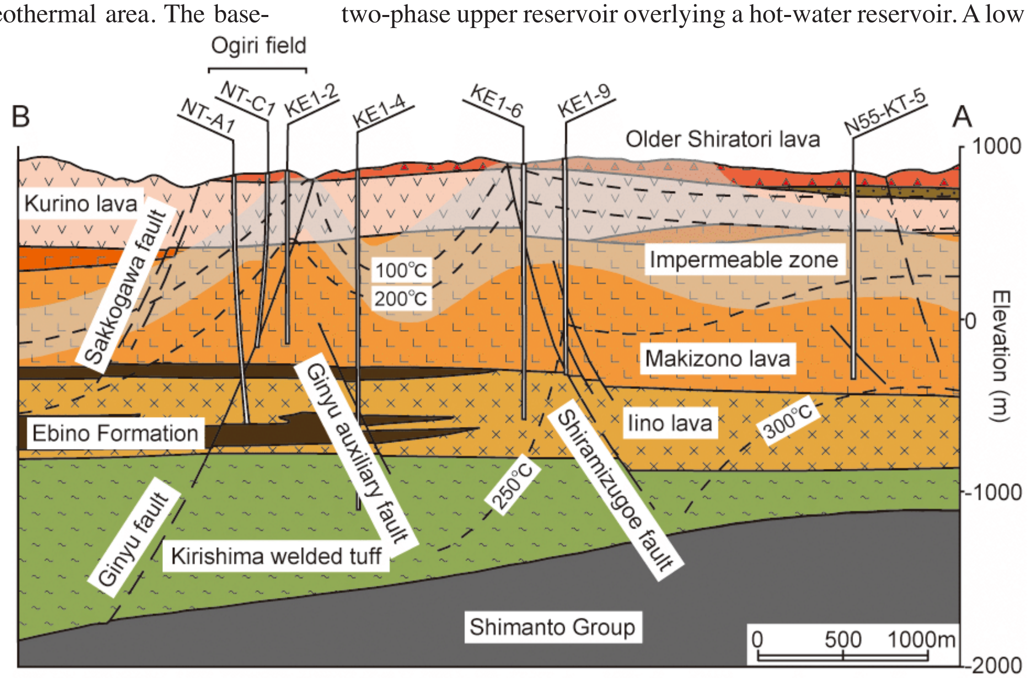

Figure 2. Geological cross section along A-B line in Fig.1 of the West Kirishima geothermal area (modified from Goko (1995, 2000)).

3. Conceptual Model

Kodama and Nakajima (1988) and Goko (2004) studied the subsurface temperature structure of the West Kirishima area including Ogiri geothermal field in detail. The temperature at depth tends to increase from west to east and southeast toward the center of the Kirishima volcanoes. It is considered that the heat sources of the West Kirishima geothermal area were formed by the volcanic activity of Kirishima volcanoes which started volcanic activities about 0.6 Ma ago (Goko, 2004). Vertical profiles of the wells located along the Ginyu fault show that temperature gradually increases from ground surface to 500m a.s.l. Then, temperature increases sharply with high gradient between 500m and 200m a.s.l. which implies that conductive heat transfer is dominant. Below this zone, temperature shows a relatively uniform value of 230°C (Kodama and Nakajima, 1988). In particular, the well bottom temperature in Well N56-KT-8 located in the southeastern part of the West Kirishima area reached about 300°C at a depth of 1800m (765m b.s.l.).

The Ginyu hot spring is located in the southern part of Ogiri and fumaroles are distributed along the Ginyu fault. Kodama and Nakajima (1988) reported the heat discharge from the ground surface of the hot spring to be 3058 kcal/s.

Geological information and the observed data of the Ogiri geothermal field show that the geothermal system consists of a two-phase upper reservoir overlying a hot-water reservoir. A low permeability confining layer separates the geothermal reservoir composed by the two-phase zone and single-phase zone from the shallow groundwater aquifer.

The Ogiri area is characterized by the presence of ENE-WSW trending faults such as Ginyu and Sakkogawa faults. The Ginyu fault zone has been one of the main reservoirs targeted for development in Ogiri (Goko, 2000; Horikoshi et al., 2005). The fault has a near planar fracture with a uniform temperature of 230°C (Goko, 2000). In addition to this, a two-phase zone is formed in the upper part of the fault. Because of its high permeability and steam cap, wells were drilled mainly along the Ginyu fault, and production and reinjection areas are located along the fault in the north-east and south-west areas, respectively. The presence of the Ginyu auxiliary fault of ENE-WSW trend with south dip was identified in the south of the Ginyu fault. Subsurface temperature of the Ginyu auxiliary fault zone is estimated to be in a range from 220°C and 240°C (Goko, 2004). It is considered that the Ginyu auxiliary fault zone has high potential to be developed as a production zone (Goko, 2004). The Sakkogawa fault located north of the Ginyu fault is considered to be a flow path of meteoric water as low temperature was measured in a well drilled along this fault (Kodama and Nakajima, 1988). The NW1 fault striking NW to SE intersects with Sakkogawa fault, Ginyu fault and Ginyu auxiliary fault. Therefore, it is concluded that the NW1 fault plays a significant role as a flow path of the high temperature geothermal fluid supplied from deep zone in the eastern part of Ogiri. Table 1 summarizes hydrogeological features of formations in the Ogiri geothermal system.

4. Grid Model

In our numerical model of the Ogiri geothermal field, a three-dimensional grid system covers an area of 9.5 km by 7.9 km with elevation 250 m a.s.l. down to 2600 m b.s.l. The sizes of the grid blocks range from 100m×100m to 3000m×3000m with thicknesses of 100 m to 1600 m. The model was divided on a horizontal plane into 23 blocks for east-west and 11 blocks for south-north directions with seven layers. The layers were named from AA to GG which represent the top and the bottom layers of the grid system, respectively. Table 2 summarizes the vertical grid geometry. The total number of the grid blocks is 1771. Areas representing the main flow paths of geothermal fluids by the Ginyu fault, the Ginyu auxiliary fault, the Sakkogawa fault and the NW1 fault were assigned with the smallest blocks. On the other hand, a larger block was used in outer regions. The grid system was tilted by 27° from the east to north so that the main fault systems in ENE – SWS directions can be represented properly with rectangular coordinates. Figure 3 depicts the plan view of the numerical model corresponding to the domain in which observed data and calculated values are compared. The codes Mulgeom and Mulgraph (O'Sullivan and Bullivant, 1995) were used as pre- and post- data processors.

Eleven(11) rock types were used in the model to assign different rock properties for the grid blocks on the basis of the hydrogeological characteristics of the Ogiri geothermal system. A vertical slice of the grid system corresponding to the geological

Table 1. Hydrogeological features of formation in the Ogiri geothermal system (modified from Kodama and Nakajima (1988)).

Name of formation	Hydrogeological feature
Older Shiratori lava – Sagari lava	Permeable with fractures such as joint
Makizono lava (Upper part – Middle part)	Fractures are cemented by alternation mineral. Play as cap rock.
Makizono lava (Lower part) – Kirishima welded tuff (Volcanic conglomerate)	Fractures are well-developed Main reservoir
Kirishima welded tuffs	Scarce fracture Presence of faults as the flow path of geothermal fluid
Shimanto Group	Presence of fracture Geothermal fluid has been stored for a long time

Table 2. Horizontal layers used in the computational grid.

Name of layer	Depth (m b.s.l.)	Thickness (m)	Depth of block center (m b.s.l.)
Top		Infinite	
AA	-250 - 0	250	-175
BB	0 - 100	100	50
CC	100 - 200	100	150
DD	200 - 400	200	300
EE	400 - 600	200	500
FF	600 - 1000	400	800
GG	1000 - 2600	1600	1800

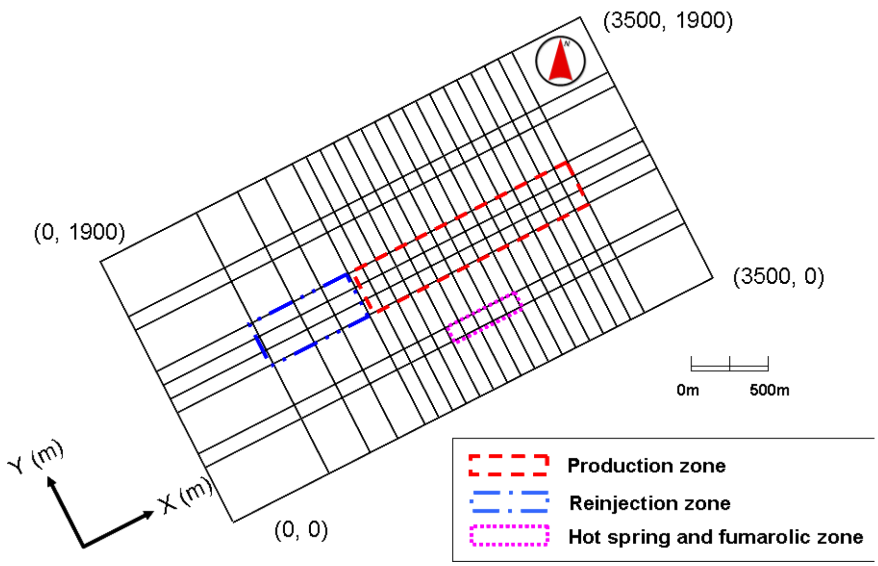

Figure 3. Plan view of the computational mesh, with close-up of the domain in which observed data and calculated values are compared.

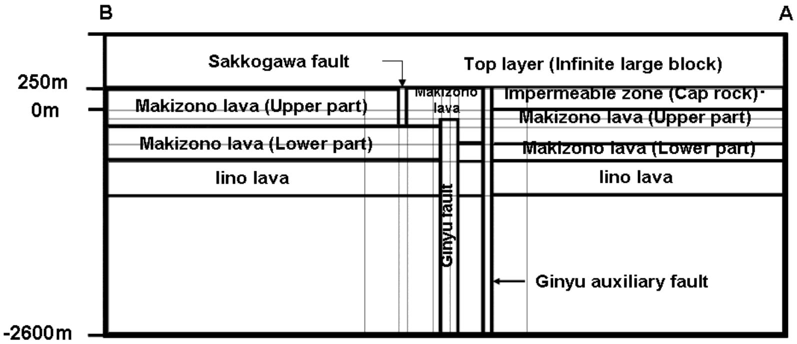

Figure 4. Vertical slice of the grid system corresponding to the line A-B of the geological cross section in Fig. 2.

Table 3. Rock parameters of the numerical model.

Rock Type	Permeability (m^2)		Thermal conductivity
	kx, ky	kz	(W/m°C)
Ginyu fault (Production area)	3.70×10^{-13}	1.21×10^{-13}	2.6
Ginyu fault (Reinjection area)	3.36×10^{-14}	3.16×10^{-16}	2.6
Ginyu auxiliary fault	3.16×10^{-16}	2.03×10^{-14}	2.6
Sakkogawa fault	3.16×10^{-16}	3.16×10^{-19}	2.6
NW1 fault	3.81×10^{-14}	7.23×10^{-15}	2.6
Impermeable zone (Cap rock)	1.70×10^{-18}	3.56×10^{-19}	1.5
Makizono lava (Upper part)	2.98×10^{-15}	3.34×10^{-19}	1.5
Makizono lava (Lower part)	4.95×10^{-15}	8.06×10^{-15}	2.6
Iino lava	2.89×10^{-16}	1.17×10^{-15}	2.6
Basement rock (Shimanto Group)	2.56×10^{-18}	1.00×10^{-14}	3.0
Top layer	1.70×10^{-18}	3.56×10^{-19}	1.5

cross section (Figure 2) is shown in Figure 4. Table 3 summarizes the permeability values and thermal conductivity of each rock type assigned to the numerical model. Kumamoto et al. (2008) investigated the rock properties in the Ogiri geothermal area in detail. The optimum values of rock permeability in the field were estimated through inverse analysis by using the code iTOUGH2 (Finsterle, 2000), therefore those values were used here in constructing the numerical model. Porosity of 10%, density of 2500 kg/m^3 and specific heat of 1050 J/kg·°C were given to all rock types.

5. Numerical Simulation

5-1. Natural State Simulation

As the first step of modeling, we developed a numerical reservoir model of the Ogiri geothermal field and carried out natural state simulation with the model using the TOUGH2 code (Pruess et al., 1999).

Natural-state modeling is essential in order to understand the field behavior before any exploitation. In addition, the natural-state model provides initial conditions for the exploitation modeling. In the process of the natural-state simulation, simulated values are dependent on boundary conditions and on the values of the reservoir parameters. Therefore, simulated results are compared against measured field data during the natural-state simulation and boundary conditions and reservoir parameters are adjusted until a satisfactory match between measured and simulated values is obtained.

During the natural-state simulation of the Ogiri geothermal reservoir, the simulated results were compared against measured temperature and pressure data in the field. The matches were improved by adjusting the permeability, fluid flow rate and enthalpy of the high-temperature recharge assigned to the bottom two grid blocks. Moreover, the location of the outflow specified at the surface of the grid model needed to be adjusted. One of the main purposes of this research was to represent the two-phase zone formed at the upper part of the geothermal reservoir with a numerical model and analyze the reservoir behavior in the zone. Therefore, the surface of the numerical model was specified 250 m a.s.l. This allowed us to focus on the analysis of two-phase zone. To represent the upper part of the Ogiri geothermal field and the atmospheric layer, an infinitely large block saturated with water at 9.807×10^4 Pa and 75°C was specified at the top of the numerical model. In addition, a low permeable rock type was assigned to the block. The lateral boundaries were set to be impermeable with respect to mass and adiabatic to heat, and large volumes were assigned to blocks along the periphery of the model. Mass recharge was specified at two blocks of the bottom layer. A mass inflow rate of 20 kg/s of enthalpy 1047.1 kJ/kg fluid was assigned for a grid block located in the eastern part and a mass inflow of 40 kg/s of enthalpy 1062.7 kJ/kg was supplied into the other block located in deep zone of the production area. The conductive heat flux of 0.432 W/m^2 was assigned to the grid blocks of the bottom layer on the south part of the Sakkogawa fault. The remaining bottom layer blocks were assigned a conductive heat flux of 0.0432 W/m^2. Consequently, the total amount of heat supplied from the bottom of the model was 19.5 MW. The initial condition was specified to be at pressure equilibrium saturated with water of temperature 15 ºC.

Surficial surveys were carried out before the geothermal power plant was installed in the Ogiri field and the survey results identified a variety of geothermal manifestations (hot springs, fumaroles etc.) at the ground surface of the area (Goko, 2000). It is considered that hot water and vapor convect upward through fractures in the cap rock. Therefore, in order to reproduce the hot spring activities in the numerical model, fluid discharges based on deliverability (Pruess et al., 1999) were utilized in nine blocks in layer AA below the locations corresponding to these surface manifestations. The productivity index (PI) was calculated using a deliverability model and the well bottom pressures (P_{wb}) were obtained by trial and error.

The natural-state simulation was carried out over two time frames. This is because we considered that natural discharge of geothermal fluid through the hot springs and fumarolic areas began under high pressure and temperature conditions. Hence, in order to obtain these conditions inside the numerical model, we first carried out the natural-state simulation over a time frame of 0.5 million years. As the second step of the simulation, PI values were specified at the top surface of the numerical model and the natural-state was simulated for another 0.5 million years.

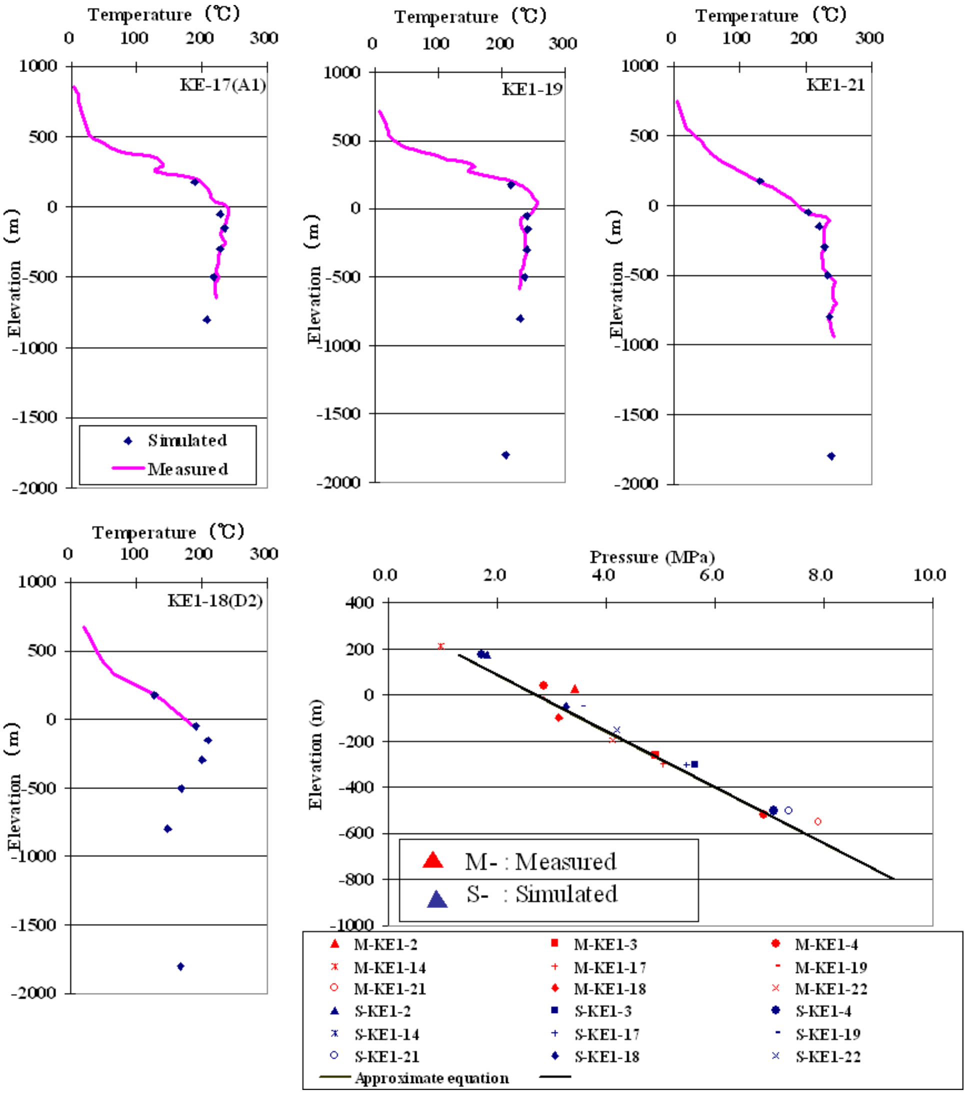

Figure 5. Comparison between measured and simulated temperature profiles of four wells located along the Ginyu fault and pressures at the main feed zones in nine Ogiri geothermal wells.

The match between the simulated and measured initial reservoir pressures at the feed points in the nine wells are presented in Figure 5. We could not compare the simulated values against the measured ones at the same elevations because simulated values given by the TOGUH2 code represent the data at the middle of each grid block. However, using the relationship between initial reservoir pressures at the feed points and the elevation, the reservoir pressures are defined as follows:

$$P = 2.71 - 8.20 * 10^{-3} * h \qquad (1)$$

where h is the altitude at which the pressures are computed. In this case, the simulated pressures were relatively well matched to the approximated ones given by Eq. (1) though the simulated values are slightly higher than the approximated values.

The simulated total discharge rate from the surface of the grid model corresponding to the hot springs and fumaroles could not be compared against measured ones because of lack of detailed information in regard to the measured values. However, the simulated total discharge rate from the numerical model was 59.7 kg/s whereas the total mass of 60.0 kg/s was recharged through the bottom layer of the grid model, so the model proposed was in material balance.

The constructed model reproduced the two-phase zone formed at the upper part of the Ogiri geothermal reservoir system in the natural-state condition and the amount of vapor was estimated to be about 1.66×10^{7} kg (2.51×10^{6} m^3) through the natural-state simulation. In addition, it was estimated that the internal energy of about 6.46×10^{19} J was stored inside the geothermal reservoir system.

5-2. Results and Discussion

The model calibration was carried out with the code TOUGH2 (Pruess et al., 1999) and the permeability of 11 rock types and enthalpy and flow rate of mass supplied at depth were estimated.

The constructed model is characterized by the presence of a high permeable zone that represents the main production zone of the Ginyu fault. Simulated results with the constructed model were compared to measured temperature profiles of four representative wells in Figure 5. Temperature profiles of the production wells located along the Ginyu fault zone, wells KE1-17, KE1-19 and KE1-21 show fairly good matches between the measured and simulated results. Well KE1-18 located in the reinjection area also shows good matches. Kodama and Nakajima (1988) reported that the main geothermal reservoir lies between 0 m to –500 m a.s.l. in Ogiri. Temperature profiles of the wells in this interval show good matches between the simulated and measured values such that all measured temperature data points (27 data points) in this zone showed relative error within 5%.

6. History Matching Simulation

6-1. History Matching Simulation

As the second step of modeling, we carried out history matching with the model constructed during the natural state simulation. The model calibration was also carried out with the code TOUGH2 (Pruess et al., 1999).

The main objectives of this simulation were to develop a numerical model that can simulate the observed data for about 22 years of production and reinjection from July 1984 to March 2006 and to analyze the reservoir behavior during exploitation. Moreover, once a plausible numerical model of the “present” state of the Ogiri geothermal reservoir has been developed, it can be used for designing future development scenarios for the field in terms of sustainability. In the process of the history matching simulation, simulated results depend on boundary conditions and on the values of the reservoir parameters. The results also depend on the natural state model. Therefore, simulated values are compared to measured field data during the history matching and boundary conditions and reservoir parameters are adjusted. Afterwards, the natural state simulation may need to be conducted again. If a reasonable initial condition is reproduced through the natural state modeling, then, the history matching simulation is carried out. These procedures are conducted repeatedly until reaching the reasonable numerical model of the present state of the geothermal reservoir system.

During the history matching simulation of the Ogiri geothermal reservoir, the simulated results were compared against measured temperature and pressure histories in the two observed wells KE1-19 and KE1-13. In addition, measured enthalpy histories in 13 wells were used to compare with simulated values through the history. The matches were improved by adjusting the permeability, fluid flow rate and enthalpy of the high-temperature recharge assigned to the bottom two grid blocks. Moreover, the location of the out flow specified to the surface of the grid model needed to be adjusted. In The Ogiri geothermal field, natural discharge of geothermal fluid through fumarolic areas seems to be less active with time. This might have been caused by mineral scaling in the surrounding formation. Therefore, we assumed there to be no natural discharge in the simulation between 2000 and 2006. For the initial condition and the boundary condition of the model, the natural state model obtained via the preexploitaion modeling was used. That is, temperature and pressure distributions in the natural state condition were utilized as the initial conditions of the subsequent exploitation modeling. Furthermore, the boundary conditions and the distributions of rock properties employed in the natural state modeling were used for the history matching simulation. We assumed that a total mass of 85 kg/s of about 240 ºC water was recharged at depth into the geothermal reservoir during the exploitation stage although a rate of 60 kg/s was assumed to be supplied into the system in the natural state condition. The increase in recharge is expected due to the reduction in reservoir pressure during exploitation. Histories of production and reinjection flow rates were assigned as input data. Figure 6 presents the flow-rate histories of the produced and reinjected water.

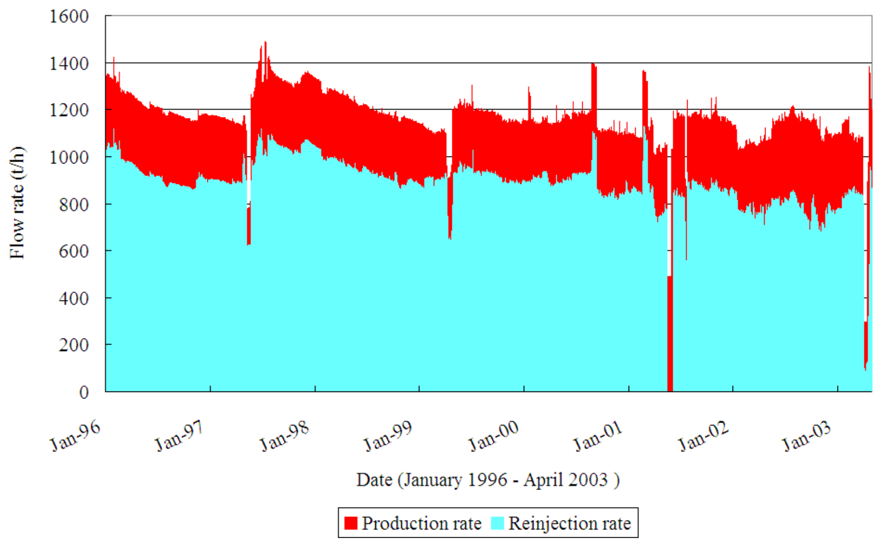

Figure 6. History of production and reinjection flow rate for Ogiri.

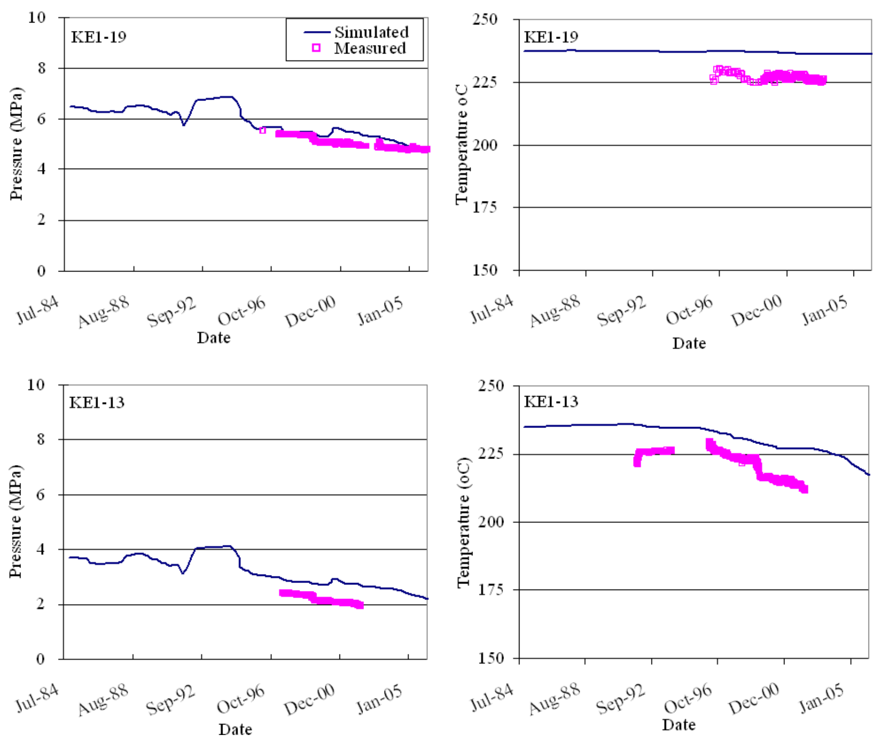

Figure 7. Comparison of computed and measured pressure and temperature histories for two Ogiri observation wells.

6-2. Results and Discussion

The model calibration was carried out with the code TOUGH2 (Pruess et al., 1999) and the observed data for about 22 years of production and reinjection from July 1984 to March 2006 was simulated with the numerical model.

Figure 7 compares the measured and computed temperature and pressure histories for two observation wells, KE1-19 and KE1-13. The feed point in KE1-19 is located in the deep hot-water reservoir. On the other hand, that in KE1-13 is situated in the two-phase upper reservoir. The well KE1-19 exhibits a reasonable match to the measured pressure history. KE1-19 also shows a good agreement between the measured and simulated temperature although there are small discrepancies. Moreover, the simulated pressure and temperature histories in well KE1-13 are matched with the measured ones, again with small discrepancies. In general,

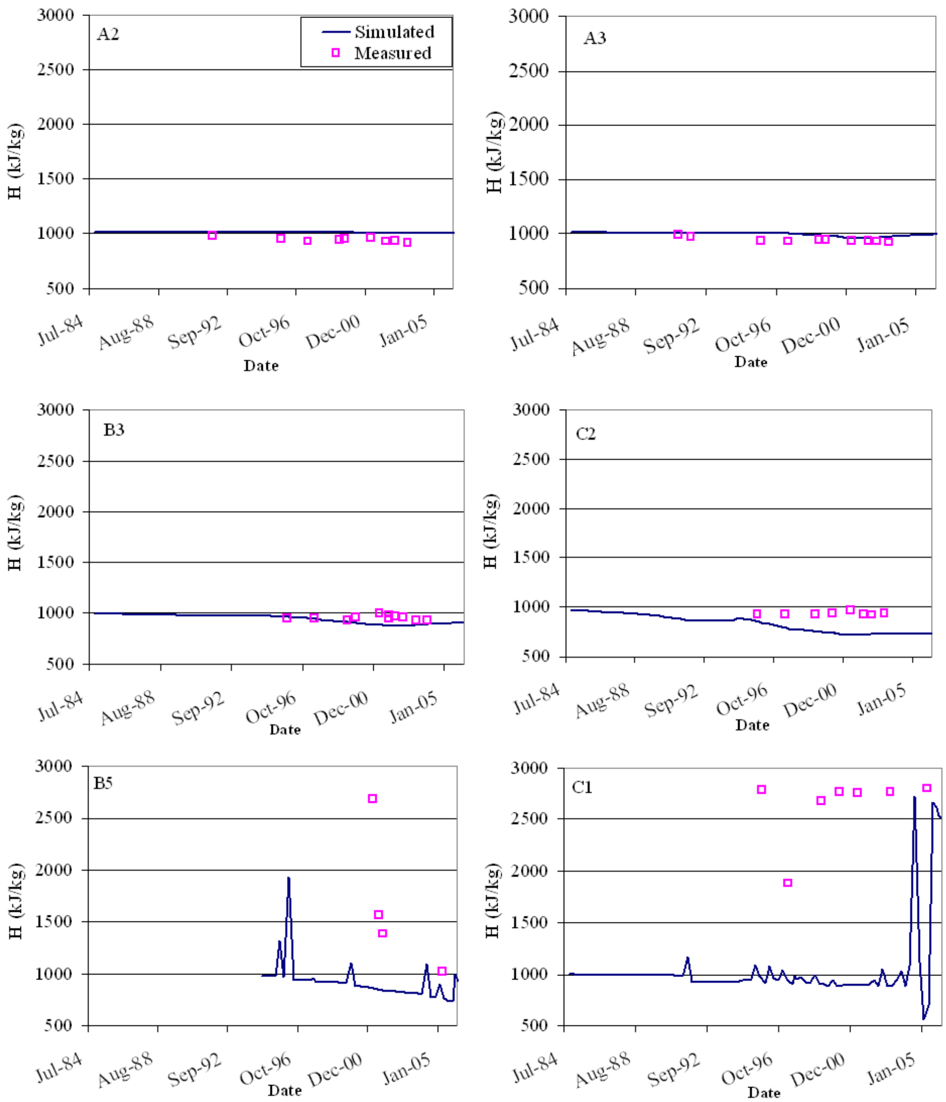

Figure 8. Comparison of measured and simulated enthalpy histories of production wells.

these results exhibit a good match in the two observation wells and represent the reservoir behavior of the Ogiri geothermal system in the exploitation stage.

Figure 8 shows a comparison of measured and simulated enthalpy (H) histories for six representative production wells (A2, A3, B3, C2, B5 and C1). The feed point in well A2 is located in the block in the layer EE and those in wells A3 and B3 are situated in the block of the layer DD. Layers CC and BB include the feed point in well C2 and those in wells B5 and C1 respectively. Measured enthalpy values for wells A2, A3, B3 and C2 are all fairly constant at about 900 – 1000 kJ/kg and they show feed temperatures of about 210 ºC – 240 ºC from liquid feedzones. Well A2 shows a reasonable match to measured enthalpy history. In this well, the measured enthalpy history shows a slight increase with time and then a decrease whereas the simulated history remains constant with time, suggesting feed temperature of about 230 ºC – 240 ºC. Also, satisfactory matches to the measured enthalpy histories are obtained for wells A3 and B3. In well A3, the measured enthalpy history exhibits constant values with time. However, the simulated values drop slightly with time after the operation of the geothermal power plant was started in 1996 and then increase. Calculations for well B3 also show a decrease with time and then an increase. On the other hand, the measured values increase between 1996 and 2001 and decrease after that period. In well B3, the biggest discrepancy observed between measured and simulated enthalpy values is about 120 kJ/kg. This indicated that the computed temperature is higher than the measured one by 35 ºC. It is considered that there are two reasons for the decreases in simulated enthalpy values; one is heat loss associated with temperature drop in boiling and the other is the effects of reinjection water. The shallow layers (AA, BB and CC) modeled the existence of two-phase conditions within the reservoir. In particular, the two-phase zone is formed at blocks immediately above those that include feed points in wells A3 and B3. Hence, it is considered that the two-phase region absorbs heat from the surrounding area and as a result the simulated enthalpy histories in wells A3 and B3 are affected slightly by the phenomenon. Furthermore, histories of reinjection flow rates are assigned as input data and colder fluid of 546.3 kJ/kg (approximately 130ºC) are reinjected from 12 wells in the south-west area (see Figure 3). We assume that injection is made into four blocks of the layer DD. According to the simulated temperature contour map in layer DD, the temperature tends to decline along the Ginyu fault from the center of the reinjection zone and it seems that the temperature drop has a negative impact on the production zone. The rock permeability values for x and y directions of the reinjection zone are larger than that for the z direction (see Table 3). Therefore, reinjection water may migrate in a horizontal direction more rapidly than in a vertical one. In well C2, discrepancies between measured and simulated enthalpy values are observed. The measurements show slight increase with time and then decrease whereas the calculations tend to drop continuously with time. The biggest discrepancy is about 240 kJ/kg, which is equivalent to a temperature difference of about 60 ºC. This is also considered to be due to the heat loss associated with the formation of the two-phase zone and the reinjection of colder fluid affecting the simulated values. Although the two-phase region was formed in layer CC as well as in layers AA and BB in the history matching simulation, the geological information and the observed data in the field assume that the steam/water interface appears at about 80 m b.s.l. (NKGC, personal communication, September 2006). This elevation is located in layer BB of the numerical model. Therefore, the two-phase region represented with the constructed model is slightly larger than the actual case. Besides, colder water is assumed to be reinjected into five blocks in the layer CC and again the temperature drop along the Ginyu fault from the center of the reinjection zone in the layer CC is observed. In particular, the block that includes the feed point in well C2 is located near the reinjection zone. Therefore, the computed enthalpy history of this block is influenced strongly by the reinjection. Measured enthalpy histories for wells B5 and especially C1 indicated discharge of dry steam. On the other hand, simulated enhtalpies show mostly liquid feeds with occasional excursions and periods of high enthalpy. It is considered that feed points in these wells are located near the steam/water interface and their enthalpy histories are affected strongly by the boiling of water and the condensation of vapor in the exploitation modeling. Although enthalpy histories at feed points in the two vapor-dominated wells show different behaviors, locations of the feed points are very close and they are located in the same gird block of the numerical model. However, for the convenience of the numerical simulation, histories of production flow rate in the two wells were assigned to different blocks as input data. Namely, the history of production flow rate in well B5 was assigned to grid block 111 in layer BB and that in well C1 was allocated to grid block 116 in layer BB. These wells show poor agreement between the simulated and measured enthalpy histories. Numerical solution of the reservoir behavior appearing near steam/water interfaces poses some difficult problems (Pruess et al., 1982). According to the literature, the reason for the difficulties is that large gradients in various parameters (e.g., pressure, saturation and boiling rate) can occur near the interface and that parameters may change rapidly with time. In porous media, there is assumed to be approximate thermodynamic equilibrium within each element because the thermodynamic conditions are regarded to vary continuously and smoothly for any small grid blocks. However, the two-phase zone and steam/water interface may appear suddenly within the developed model and we have to estimate the behavior accurately. Therefore, it is suggested that reservoir behavior around the two-phase region may be analyzed further by the introduction other methods, for example, better vertical resolution near the boiling interfaces and use of the MINC method (Pruess, 1983) to better represent the transient two-phase flow.

Production rate decreased with time after the operation of the geothermal power plant was started in the Ogiri area. Therefore, additional production wells were drilled to maintain steam production for 30 MWe. The cause of depletion of the geothermal reservoir is considered to be pressure and temperature drops inside the reservoir system (Horikoshi et al., 2005). Hence, we will discuss these phenomena, based on our history matching simulation. The Ogiri geothermal field is composed of a two-phase upper reservoir and a hot water reservoir below. Therefore, it is considered that there are two reasons for pressure and temperature decline in the reservoir system; one is heat loss related to temperature drop in the boiling zone and the other is mass loss associated with production of the geothermal fluid.

For the upper two-phase reservoir, it is considered that pressure and temperature declined because of heat loss. The developed numerical model of the "present" (2006) state of the Ogiri geothermal reservoir reproduces the steam cap formed at the upper part of the field. The amount of vapor in the present state was estimated to be about 5.16×10^7 kg (4.29×10^6 m^3) through the history matching simulation. In addition, it was estimated that an internal energy of about 6.46×10^{19} J was stored inside the geothermal reservoir system in the present condition. From these results, it is estimated that there has been an increase of about 3.50×10^7kg (1.78×10^6 m^3) in the amount of vapor during the exploitation. Hence, it is concluded that the two-phase region expands due to the development of the Ogiri geothermal reservoir. On the other hand, the internal energy decreases by 4.70×10^{16} J during the exploitation of the field. Assuming that total steam of about 275 t/h at about 2803.1 kJ/kg (approximately 240 ºC) was produced and total mass of about 875 t/h at about 546.4 kJ/kg (approximately. 130 ºC) was injected between 1996 and 2006, the heat loss upon the development is about 2.56×10^{16} J. This involves a number of approximations because the hot-water recharge from the bottom of the numerical model and outflow from the surface were specified in the process of history matching. However, this estimation can provide an important clue that production of the geothermal fluid is not the sole cause of the loss of internal energy. Therefore, it is considered that the internal energy inside the reservoir dropped with expansion of the two-phase zone and that pressure, especially in the upper part, decreased due to heat loss associated with temperature drop during boiling around the two-phase zone.

For the deep hot-water reservoir, it is considered that pressure and temperature declined because of mass loss. The difference of production and reinjection flow rate in the exploitation stage is about 300 t/h (see Figure 6). Taking into account hot-water recharge in the deep zone and outflow through the hot springs and fumarolic areas, there is a difference of about 163 t/h between inflow into and outflow from the geothermal reservoir. We specified that the total mass of 85 kg/s (about 306 t/h) is recharged at depth in the Ogiri geothermal reservoir system during exploitation. On the other hand, outflow of 47 kg/s (about 169 t/h) through the surface of the numerical model is assumed in the history matching simulation between 1984 and 2000. Although geothermal manifestations at the ground surface of the Ogiri area decrease gradually with time after the development, we at first specified the outflow between 1984 and 2006 in the numerical model. However, pressure and temperature in the upper part of the model decreased after the production history of well C3 was specified as input data. Moreover, that caused the model calibration to deviate significantly from a match. The well C3 was drilled in 2003 and started operation in 2004. However, field observations did not indicate that pressure and temperature in the reservoir declined dramatically after the operation of well C3 was started. Therefore, in order to consider this phenomenon in the numerical model, we first specified the outflow at the top surface of the numerical model and carried out the history matching simulation between 1984 and 2000. As the second step, we assumed there to be no natural discharge after 2001 and continued the simulation between 2001 and 2006. Under this scenario, simulated pressure and temperature histories replicated the geothermal reservoir behavior, namely decline of pressure and temperature with time in wells KE1-13 and KE1-19. From these trials, we found that material balance of the geothermal reservoir had a strong influence on its pressure and temperature behaviors. Measured pressure and temperature in the Ogiri geothermal field decrease gradually in the exploitation stage. Therefore, production/reinjection scenarios need to be reviewed in order to prevent depletion of the Ogiri geothermal reservoir and achieve its sustainable development.

As a result of the exploitation modeling, the developed numerical model provides a good overall match to measured temperature, pressure and enthalpy histories. That confirms that the constructed model could be utilized for the future prediction of the reservoir performance.

7. Conclusions

The results of our numerical modeling study can be summarized as follows:

A three-dimensional numerical reservoir model of the Ogiri geothermal field was developed to simulate both its preexploitation and exploitation stages using the code TOUGH2.

A natural-state simulation was conducted to match the temperature profiles in 11 wells and a reservoir pressure profile measured under undistributed (preexploitaion) conditions. Relatively good agreement was obtained between the measured and computed temperature and pressure profiles.

The constructed model successfully reproduced the two-phase zone formed at the upper parts of the Ogiri geothermal reservoir system in the natural-state condition. The amount of vapor was estimated to be about 1.66×10^7 kg (2.51×10^6 m^3) under natural conditions. Moreover, it was estimated that the internal energy of about 6.46×10^{19} J was stored inside the geothermal reservoir system.

The developed model provided a good overall match to measured temperature, pressure and enthalpy histories in the process of the exploitation modeling. However, the simulated enthalpy histories in the vapor-dominated wells, namely B5 and C1 showed poorer matches.

It was estimated that during the exploitation the amount of vapor increased about 3.50×10^7 kg (1.78×10^6 m^3) and the internal energy decreased about 4.70×10^{16} J.

The causes of pressure decrease inside the Ogiri geothermal reservoir were assumed to be heat loss associated temperature drop in boiling induced by expansion of the two-phase zone and mass loss upon production of geothermal fluid.

The constructed model could be used for future prediction of the reservoir performance.

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