Numerical modeling of hydrothermal systems at the Appi field, Iwate, Japan

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ABSTRACT

The Appi field is one of the promising geothermal fields in Japan. A high temperature reservoir is present below thick impermeable layers and vapor-dominated zone is found in the southwestern portion of the reservoir. Based on various geological, geochemical and geophysical surveys and deep well drilling and testing, Mitsubishi Materials Corporation (MMC) has developed a three-dimensional numerical model of the reservoir ("MMC2014" model) to examine the optimum development scale. In this research, we extended the MMC2014 model, the upper surface of which is located at ~500-m depth, to the ground surface to include shallow groundwater systems and reproduced a steam-heated hot spring in the area. We need to assign highly anisotropic permeabilities to shallow formations to reproduce relatively low feed point pressures of deep wells (~8 MPa at depth of 1,500 meters). Based upon the natural state model, we carried out performance prediction and calculated its effects on the thermal conditions of the hot spring. Simulation results indicate that present production plan enables stable power generation of 15 MW for 30 years, and have little effect on the thermal conditions of the hot spring.

1. INTRODUCTION

For geothermal power generation, numerical modeling is often used to predict reservoir behavior and examine the optimum development scale. It is necessary to model not only reservoir depth regions but also shallow ground water systems to investigate fluid recharge during fluid production and the effects of production on shallow ground water systems such as a hot spring. In addition, prediction of changes in geophysical observables such as gravity, electrical resistivity and self-potential caused by the fluid production can contribute to designing a monitoring plan.

In this study, we extended a numerical model of hydrothermal system to include shallow ground water system at the Appi field, which is one of the promising geothermal fields in Japan (Figure 1). A high temperature reservoir is present in the Middle Aniai Formation below thick impermeable layers (Upper Aniai Formation) and vapor-dominated zone is found in the southwestern portion of the reservoir. The maximum temperature is 349.9 °C at 2,165-m measured depth of an exploratory well AP-5 penetrating the southeastern relatively low permeability region. We reproduced temperature and pressure data from various deep wells, and a steam-heated hot spring at the natural state. Then we carried out performance prediction and calculated its effects on the thermal condition of the hot spring.

2. MODEL SETUP

2.1 Base model (MMC2014 model)

Based upon New Energy and Industrial Technology Development Organization (NEDO)'s surveys and modeling (Ariki et al., 2006; Kato et al., 2006), Mitsubishi Materials Corporation (MMC) has developed a three-dimensional numerical model of the reservoir to examine the optimum development scale ("MMC2014" model, Nomura and Kato, 2015; see Figure 2). The model set its top surface at around 500-m below the ground surface, and assumed the constant pressure (0.1 MPa) as the top boundary condition. Low-permeable Upper Aniai Formation lies around the top surface of the model, which allows the top surface at 500-m depth to reproduce the reservoir behavior. However, it is necessary to include shallow formations to investigate the recharge from the shallow ground water systems and effects of power generation on hot-springs. In this study, we extended the MMC2014 model to the ground surface to include shallow ground water system and a hot-spring.

2.2 Model extension to ground surface (OCT2017 model)

Based upon MMC2014 model, we extended the model to the ground surface (15°C, 0.1 MPa) to include shallow formations corresponding to younger stage volcanic rocks with thickness of about 500-m. Results of about 30-case parameter studies on key parameters such as permeability indicate that it is necessary to extend the model to the northward low-elevation area, and to assign highly anisotropic permeabilities to shallow formations to reproduce low feed point pressures of deep wells (~8 MPa at depth of 1,500 meters). Such highly anisotropic structure probably corresponds to the existence of thin low-permeable layers between high-permeable formations in the field. Figure 3 shows the outline of the grid system and rock phase distribution of the extended model "OCT2017". The model size is 0.9 km × 1.05 km × 3.05 km with 12 × 17 × 20 grids.

2.3 Model extension to include a steam-heated hot spring (JAN2018 model)

Based upon OCT2017 model, we extended the model again, to reproduce a steam-heated hot spring within the model domain. There are three hot springs in the Appi field; Kusanoyu, Shin-Kusanoyu, and Appi hot spring. In this study, we include only Kusanoyu in the numerical model at $(i, j) = (4, 6)$. Shin-Kusanoyu, which is not a natural discharge, and Appi hot spring, which is spatially separated from the planned production-injection area by low permeable zone, are out of consideration in the present modelling.

Figure 4 shows the extended model ("JAN2018" model). We modified the spatial distribution of high-permeable up-flow channel from the deep heat source to the reservoir, and set another high-permeable channel from the southern end of the reservoir to the ground surface beneath the Kusanoyu hotspring. Table 1 summarizes the rock properties of each rock type.
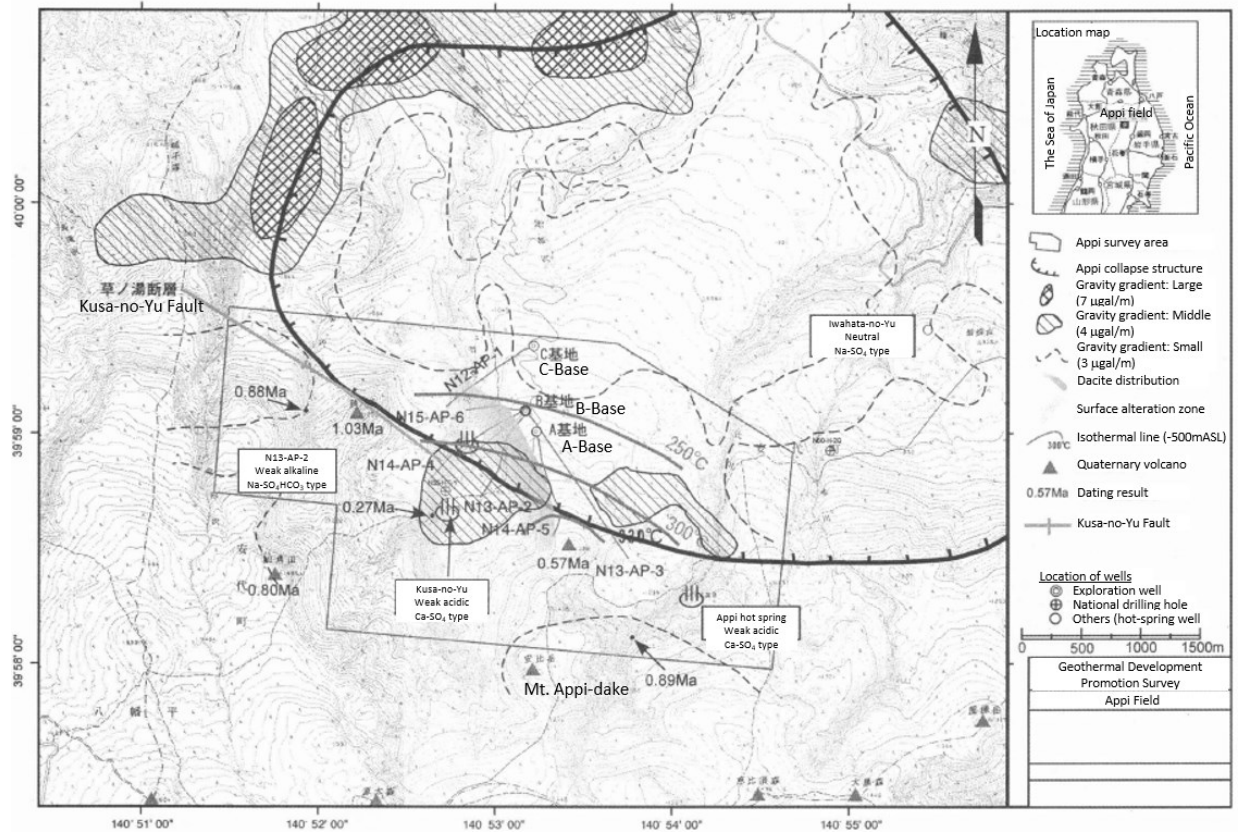
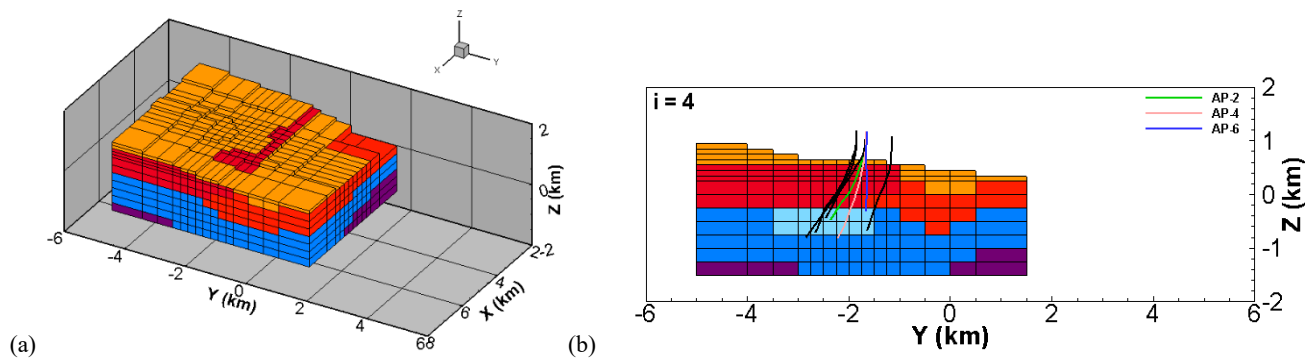**Figure 1: Map of the Appi geothermal filed showing NEDO's survey area, modified from Ariki et al. (2006).**

Figure 2: Outline of the grid system and rock type distribution of MMC2014 model, (a) 3D diagram and (b) i = 4 vertical plane. Pale blue region indicates the reservoir, high-permeable zone of Middle Aniai Formation.
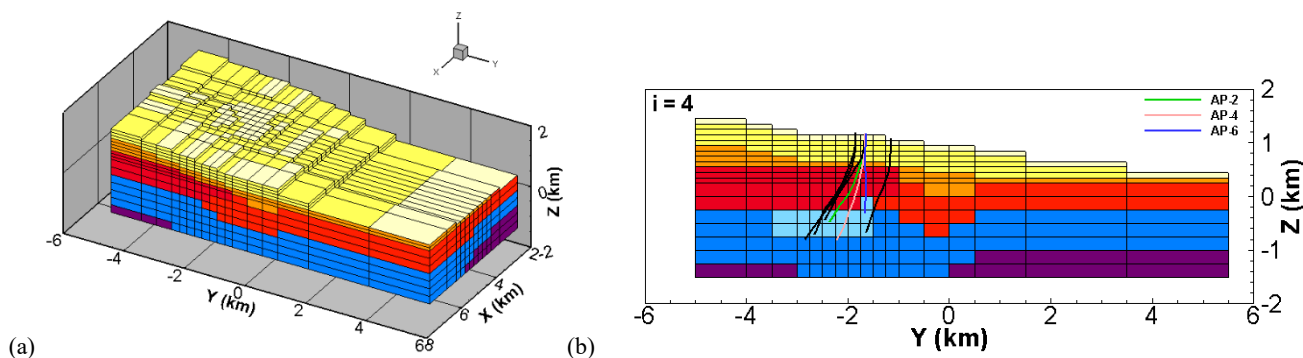
Figure 3: Outline of the grid system and rock type distribution of OCT2017 model, (a) 3D diagram and (b) i = 4 vertical plane. Yellow region indicates added formations of younger stage volcanic rock.
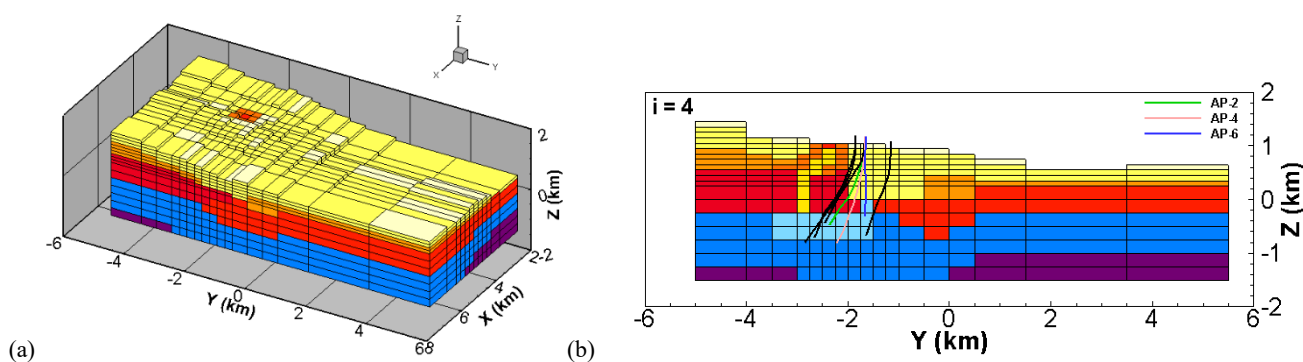

Figure 4: Outline of the grid system and rock type distribution of JAN2018 model, (a) 3D diagram and (b) i = 4 vertical plane. High-permeable channel is set from the southern end of the reservoir to the ground surface beneath Kusanoyu.

Table 1: Rock properties

	Rock type	Horizontal permeability (m²)	Vertical permeability (m²)	Porosity	Density (kg/m³)	Heat conductivity (W/K-m)
Younger stage volcanic rock		1.0×10^{-13}	1.0×10^{-14}	0.18	2,270	0.83
		1.0×10^{-13}	1.0×10^{-16}			
Pyroclastic sediment		1.0×10^{-13}	1.0×10^{-16}	0.18	2,270	0.83
Upper Aniai Fm.		2.0×10^{-17}	2.0×10^{-17}	0.11	2,460	1.35
		2.5×10^{-16}	2.5×10^{-16}			
Middle Aniai Fm.		2.5×10^{-15}	2.5×10^{-15}	0.06	2,460	2.33
		2.5×10^{-16}	2.5×10^{-16}			
		2.0×10^{-17}	2.0×10^{-17}			
Paleogene sediment		2.0×10^{-17}	2.0×10^{-17}	0.01	2,640	3.58

3. SIMULATION RESULTS OF HYDROTHERMAL SYSTEM

Using JAN2018 model, we conducted parameter studies to reproduce pressure and temperature data of deep wells, and upward total heat discharge (sum of convective and conductive heat flux) at the lower interface of the topmost block, that is, (i, j, k)= (4, 6, 15) located at Kusanoyu. Investigated parameters include permeability of the channel, thermal conditions of deep source, etc. Figure 5 shows the mass flow and heat flux sources at the bottom of the model. Based upon the natural state model, we carried out performance prediction and calculated its effects on thermal conditions of Kusanoyu. We use STAR (version 11) reservoir simulator (Pritchett, 2002) and equation o state package BRNGAS (modified in 2017 to deal with temperatures upto 370 °C, P ≤ 200 MPa) for the simulations. The package can deal with solid-gaseous-aqueous three phases and three components; water, NaCl, and non-considensible gas (air or CO_2).

(a)   (b)
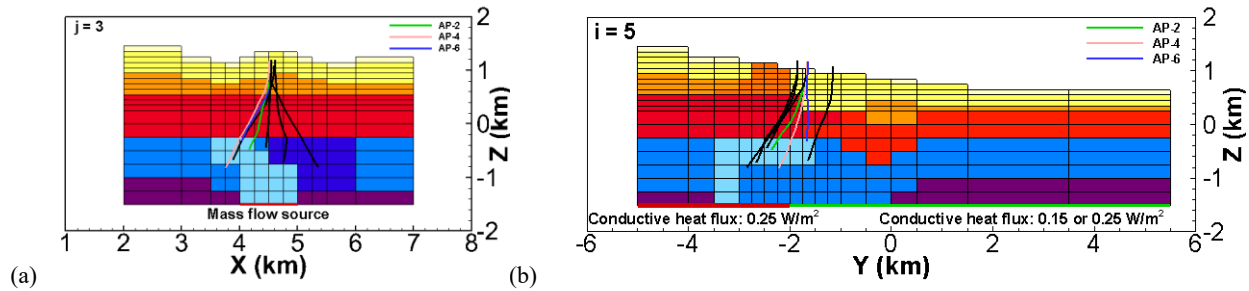
Figure 5: Deep heat source at the bottom plane of JAN2018 model (a) Mass flow source at j = 3 vertical plane and (b) heat flux source at I = 5 vertical plane

3.1 Natural state simulation

Here we describe the results of three cases with different deep recharge boundary conditions. As shown in Table 2, two mass flow rate: 2.5 kg/s or 1.5 kg/s of hot fluid (internal energy of 2,500 kJ/kg) and two different conductive heat flux for northern part of the model (j ≥ 8): 0.15 W/m^2 or 0.25 W/m^2 (this case is indicated as "+ cd hf" case in in Figures 6 and 7, Figures 9 through 16, and Figures 17 through 19) are considered. We assumed the same heat flux of 0.25 W/m^2 to the southern part of the model (j ≤ 7) and the same rock properties as the reservoir (high-permeable zone of Middle Aniai Formation) to that of the Kusanoyu channel.

As mentioned above, there are three hot springs in the Appi field, and the observed total discharge is 10.45 k/s of 34.3 °C fluid. All of them are steam-heated hot springs and considered to be formed by diluting upward steam with shallow ground water. If we assume that the ground water at 15 °C and 88 kPa (specific enthalpy 63.1 kJ/kg) is heated to be 34.3 °C, we need 0.31 kg/s flow of hot steam with 2,700 kJ/kg of specific enthalpy, which is equivalent to 817 kW heat discharge. For the present model, simulated heat discharge at Kusanoyu provides about 30% -70% of 817 kW (Table 2).

Figure 6 shows the observed and calculated pressure of the wells. Most of the pressure at the depth of the reservoir show good agreement. Wells AP-4 and AP-2 are thought to be located in a local vapor zone from the results of production tests, however, the present coarse grid model cannot reproduce it adequately. As for shallow well H-20, calculated pressures are substantially lower than the observed values. This discrepancy can be decreased by further adjusting of the permeabilities of shallower formations.

Figure 7 shows the observed and calculated temperature profiles for various wells. They show relatively good agreements except for the deepest part of AP-3 and AP-5, which show conductive profile in the deep impermeable formation.

Table 2: Mass flow rate of hot fluid (specific internal energy: 2,500 kJ/kg) and conductive upward heat flow for j ≥ 8 at the bottom surface of the model and calculated steam upflow and total heat discharge at Kusanoyu:(i, j, k) = (4, 6, 14.5)

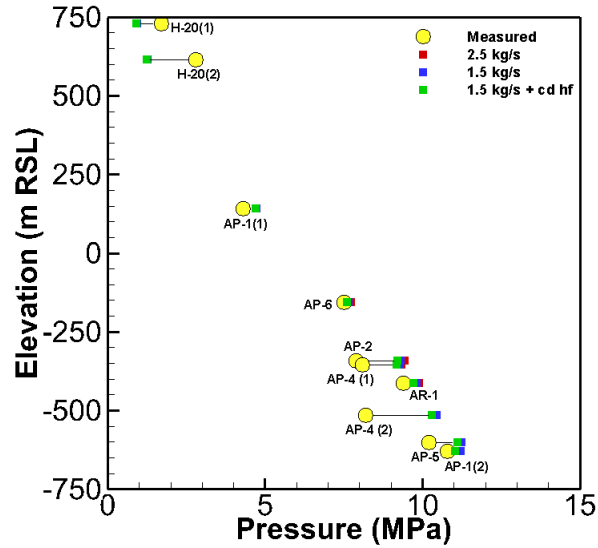| Mass flow (kg/s)	Heat flux for j ≥ 8 (W/m²)	Upflow steam flow at Kusanoyu (kg/s)	Upflow heat discharge at Kusanoyu (kW)	Estimated ratio of heat supply in the area
2.5	0.15	1.15×10^{-1}	583	0.71
1.5	0.15	4.11×10^{-3}	236	0.29
1.5	0.25	3.13×10^{-2}	322	0.39

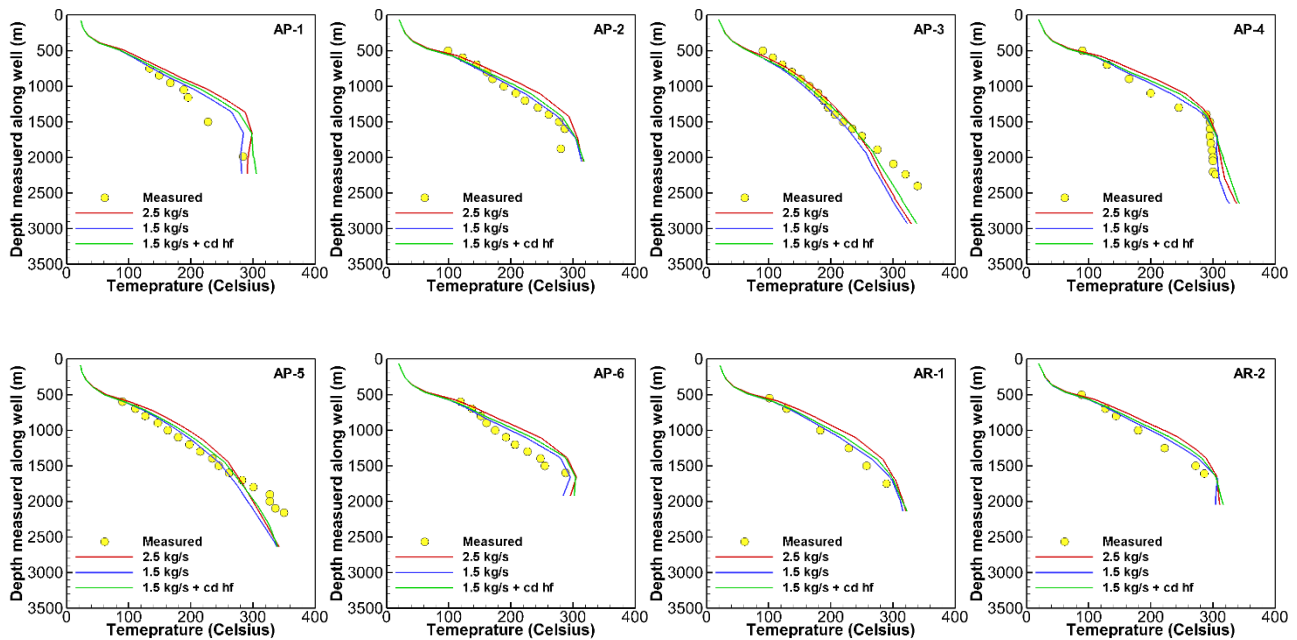**Figure 6: Observed and calculated pressure for various wells**

Figure 7: Observed and calculated temperature profile for various wells

3.2 Geothermal power generation and ground water system

Based upon the natural state model, we carried out performance prediction and calculated its effects on thermal conditions of Kusanoyu. Figure 8 shows the fluid flow schematic diagram of the planned power station. Desired output is 15 MW for 30 years. Using the final state of natural state modeling as the initial condition, we carried out performance prediction by assigning MINC double-porosity medium in addition to porous medium (Table 3) to reservoir rocks and steam flow channel to Kusanoyu.
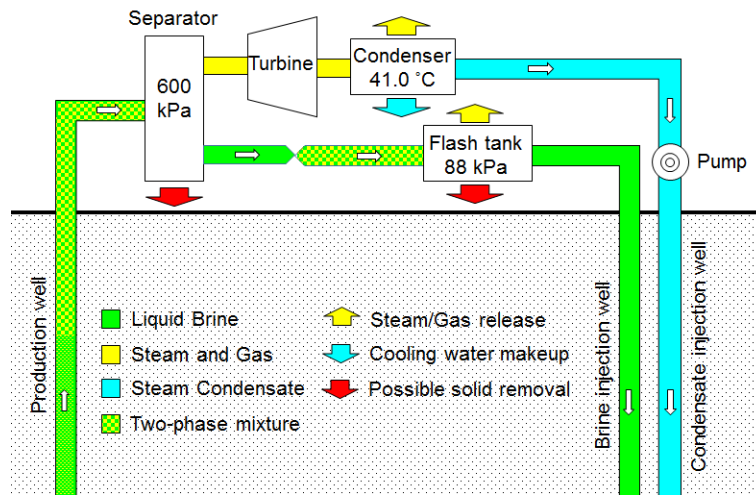
Figure 8: Fluid flow schematic diagram of the planned power station

Table 3: Parameters for MINC double-porosity model

Fracture spacing (m)	Volume fraction of fracture	Permeability of matrix (m^2)
10	0.1	1.0×10^{-19}

3.2.1 Performance prediction of geothermal power generation

Simulation results indicate that stable power generation of 15 MW for 30 years is possible for all of the cases considered here. Figures 9 through 13 show the calculated results. As shown in Figure 9, produced fluid enthalpy is higher for the MINC medium case than for the porous medium case at early several years. As for required number of the injection wells, it is less for the MINC model than for the porous model. Figures 14 to 16 show the time histories of pressure at the feed-point of AP-4, AP-2, and AP-6. Calculated results indicate maximum pressure drop of about 4 MPa after 30 years of fluid production.
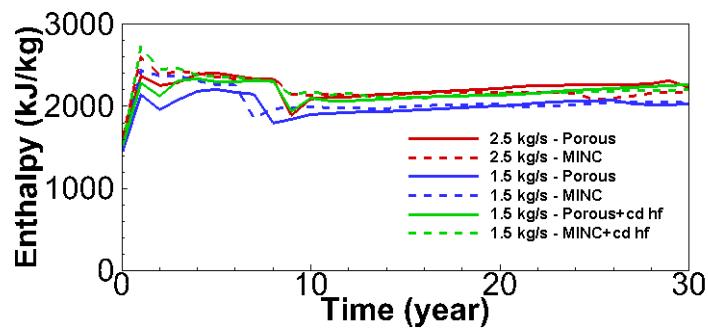
Figure 9: Time history of enthalpy of produced fluid
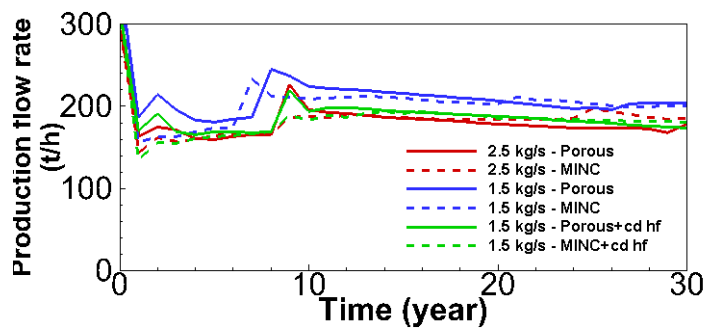
Figure 10: Time history of production flow rate
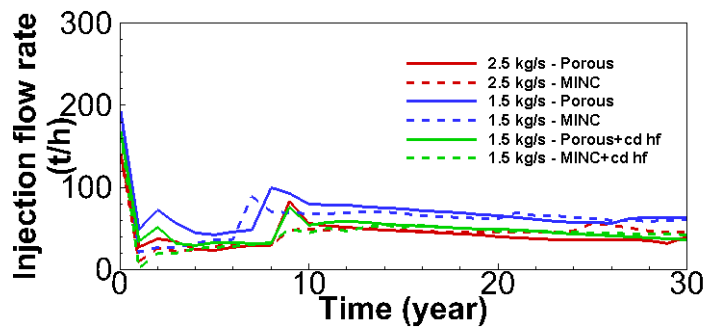
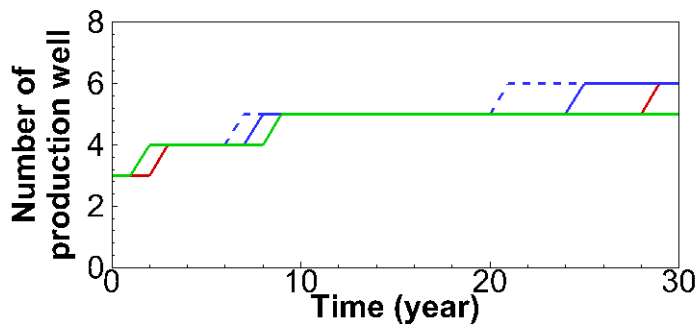Figure 11: Time history of injection flow rate

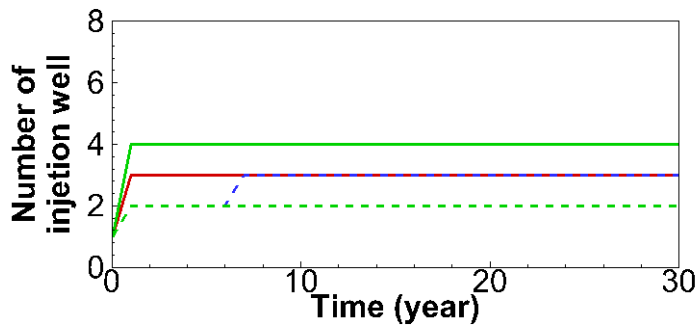Figure 12: Time history of number of required production wells

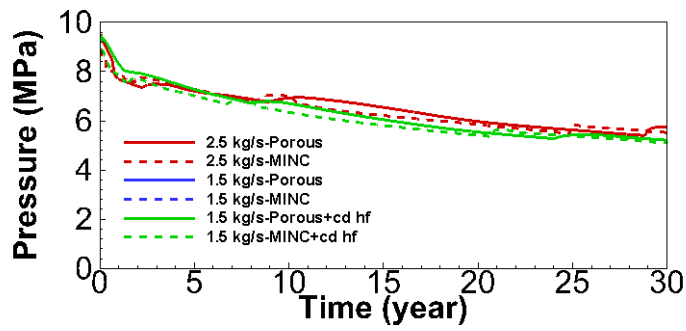Figure 13: Time history of number of required injection wells

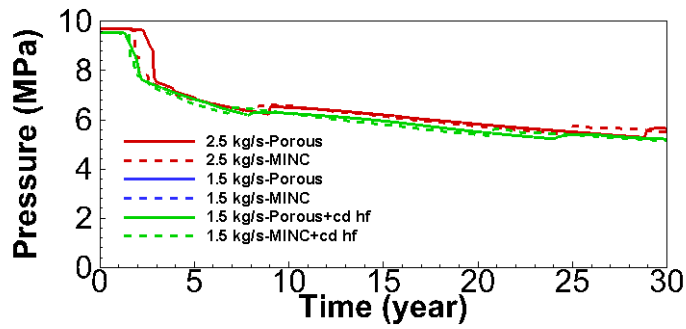**Figure 14: Time history of feed-point pressure at AP-4 feedpoint**

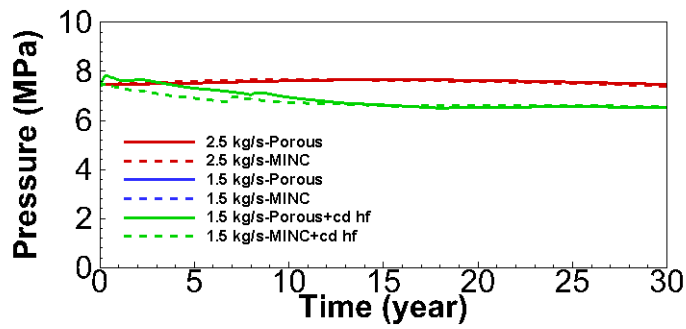**Figure 15: Time history of feed-point pressure at AP-2 feedpoint**

Figure 16: Time history of feed-point pressure at AP-6 feedpoint

3.2.2 Changes in thermal conditions of Kusanoyu hotspring

Figures 17 through 19 show the time histories of the thermal conditions at the lower adjacent block to the topmost computational block where Kusanoyu is located. (As for the topmost block the temperature is maintained at 20 °C because of conductive-radiative condition assignment). In spite of a few MPa pressure-drop at the feed-point of deep wells for 30 years of power generation, total heat discharge and gas saturation at Kusanoyu show slight decrease only for the MINC medium cases. Their decreases are so small that the temperature of the block is maintained almost constant in all of the present cases. It indicates that the present production plan has little effect on shallow groundwater systems.
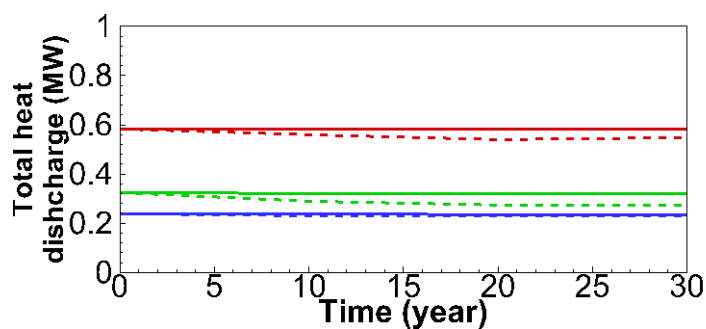
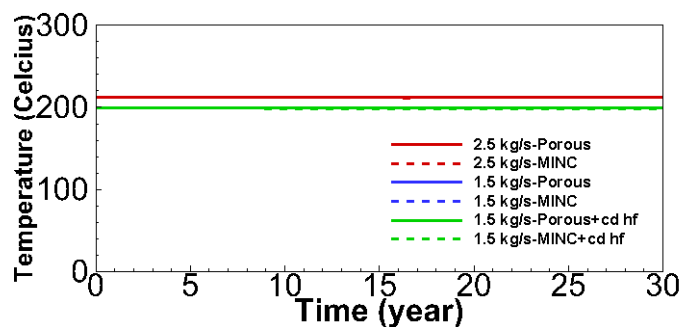**Figure 17: Time history of total heat discharge at Kusanoyu:(i, j, k) = (4, 6, 14.5)**

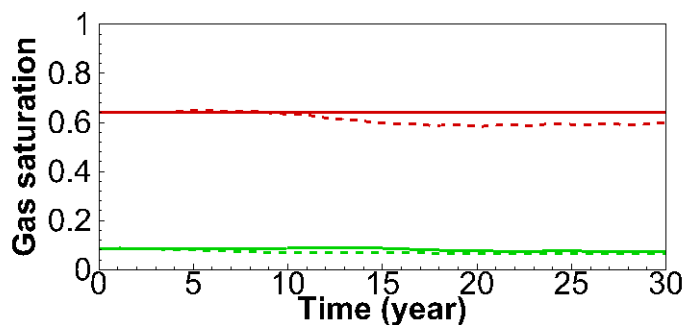**Figure 18: Time history of temperature at Kusanoyu: (i, j, k) = (4, 6, 14)**

Figure 19: Time history of gas saturation at Kusanoyu: (i, j, k) = (4, 6, 14)

3.3 Self-potential calculation

In August 2015, we carried out SP profiling along the route from Kusanoyu to the north of the B well-site ("Kusanoyu" – "B-site" – "north-end" shown in Figure 20). We applied the SP postprocessor (Ishido and Pritchett, 1999) to the natural state model (model of 2.5 kg/s mass flow in Table 2). The calculated SP profile is shown in Figure 21. After adjustments of pertinent parameters such as fluid and rock conductivities and the zeta potential, the observed data is roughly reproduced in the calculation. As seen in Figure 22, SP on the ground surface is created mainly by shallow ground water flow. We need further calculations to make a plan of SP monitoring for the Appi field.
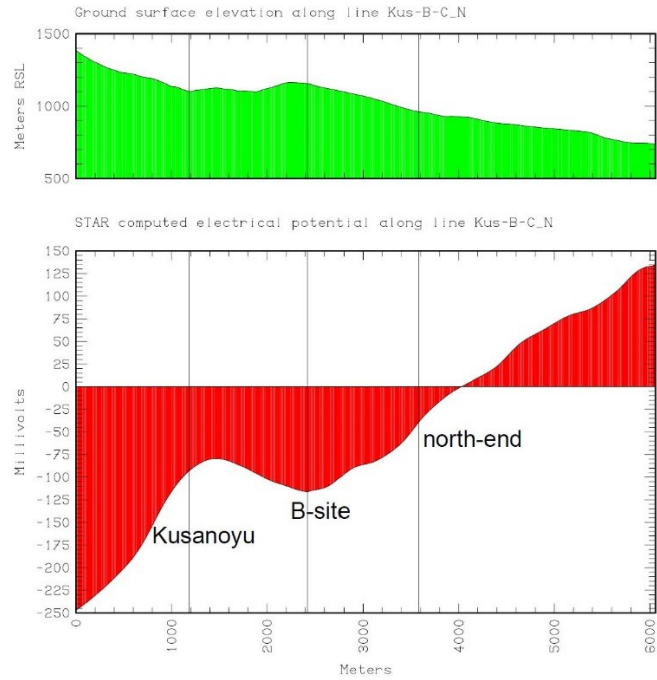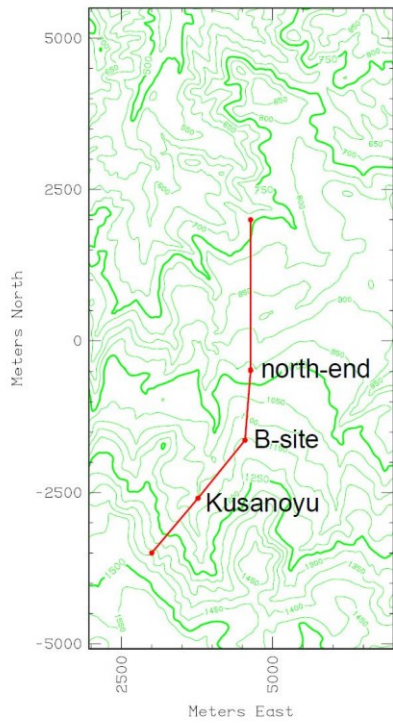
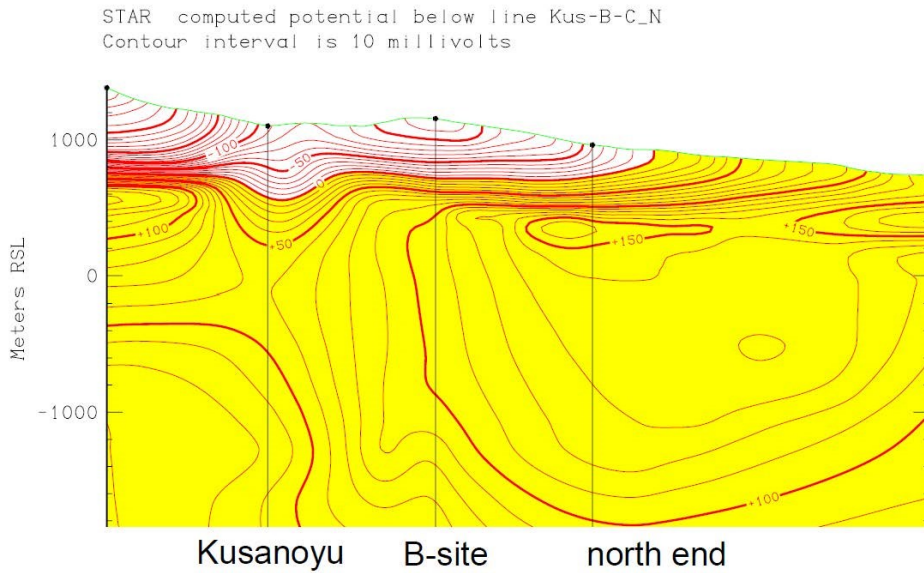**Figure 20: SP survey line used for 2015 profiling.** **Figure 21: Calculated SP profile for the natural state mode.**

Figure 22: Calculated potential distribution on a vertical section along the survey line.

4. CONLCUSIONS

In this study, we extended a numerical model of hydrothermal system at the Appi field to include shallow groundwater system and reproduce steam-heated hot springs in the area. Using the present model, we carried out performance prediction and calculated its effects on a hot spring. Simulation results indicate that present production plan enables stable power generation of 15 MW for 30 years, and have little effect on the thermal conditions of the hot spring.

REFERENCES

Kato, H., Kitao, K., Kumagai, N., Takahashi, H., Kudo, S., and Abe, Y: Reservoir Assessment of the Appi Geothermal Field, NEDO's Project "Geothermal Development Promotion Survey", Journal of the Geothermal Research Society of Japan 28(1), (2006), 3-18 (in Japanese with English abstract).

Ishido, T., and Pritchett, J.W.: Numerical simulation of electrokinetic potentials associated with subsurface fluid flow, *J. Geophys. Res.* **104**, 1999, pp. 15247–15259.

Ariki, K., Kudo, S., and Abe, Y.: Reservoir Modeling of the Appi Geothermal Field, Geothermal Development Promotion Survey (NEDO), Journal of the Geothermal Research Society of Japan 28(1), (2006), 19-36 (in Japanese with English abstract).

Nomura, Y. and Kato, H.: Reservoir modeling in the Appi field, *Abstracts*, 2015 Annual Meeting of the Geothermal Research Society of Japan, B70 (2015). (in Japanese).

Pritchett, J.W.: STAR user's manual version 9.0. SAIC Report Number 02/1055 (2002).