Development of Numerical Model of Takigami Geothermal Reservoir, Kyushu, Japan, Using iTOUGH2 Simulator

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DEVELOPMENT OF NUMERICAL MODEL OF TAKIGAMI GEOTHERMAL RESERVOIR, KYUSHU, JAPAN, USING ITOUGH2 SIMULATOR

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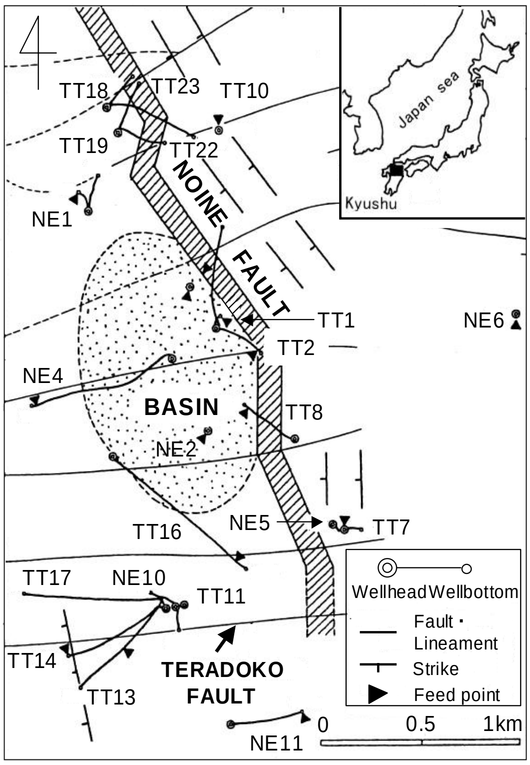
SUMMARY – A three dimensional numerical reservoir model of the Takigami geothermal field was developed by inverse analysis method. The model was calibrated by using iTOUGH2 simulator that improves a set of reservoir parameters simultaneously. Natural state, production and reinjection histories were sequentially simulated. Initial temperatures from 21 wells were matched with a numerical model in the natural state simulation process and discharged enthalpies from five production wells about 11 years in the exploitation history. A good agreement was obtained for initial temperature profiles and discharged enthalpies of production wells with the model.

1. INTRODUCTION

The Takigami geothermal field is located in the southwestern part of Oita prefecture, Kyushu Island, Japan. The Takigami power station started an operation in November 1996 with installed capacity of 25 MWe. Five production wells are located in the southwest; seven to ten reinjection wells in the north of the field. Idemitsu Oita Geothermal Co., Ltd is in charge of production and reinjection operations and supplies separated steam to the power station that is operated by Kyushu Electric Power Co., Inc.

Takigami area is surrounded by the late Pleistocene volcanoes in the Beppu-Shimabara Graven, which traverses middle Kyushu from east to west. This water-dominated field is characterized by the absence of surface geothermal manifestations such as hot spring and fumarole. There are a number of E-W, NW-SE, and N-S trending faults/fractures (Fig. 1). The N-S trending Noine fault is important because it divides the area into eastern and western parts. The E-W trending faults such as Teradoko fault are estimated to have a small vertical displacement. High permeability zone and feed zone of the wells appear along these fault sets (Hayashi et al., 1988).
Geological structure of the Takigami geothermal field is as follows (Hayashi et al., 1988). A thick layer of Quaternary volcanic and associated rocks overlies the Tertiary Mizuwake Andesite, which is estimated to overlay the basement. The Quaternary volcanic rocks are classified into four formations from top to bottom, the Noine-dake volcanic rocks, Kusu, Ajibaru and Takigami formations. These units consist of layers of andesitic and dacitic volcanic rocks. Mizuwake andesite is composed mainly of altered andesite lava flows and pyroclastic rocks.



The thermal structure of this field is basically composed three layers (Furuya et al., 2000). The first layer is isothermal (50 °C). The second layer is impermeable and has a seep and constant thermal gradient. The third layer is characterized by high temperature that ranges from 160 °C in the northeast to 250 °C in the southwest

Fig. 1 Location of Takigami geothermal field and conceptual geological structure.

It requires a large amount of time and manpower to construct a reliable numerical reservoir model by conventional analysis method (e.g. parameter estimation in a trial-and-error manner). Objectives of this study are to construct a numerical model of the Takigami geothermal field by inverse analysis method.

2. METHOD

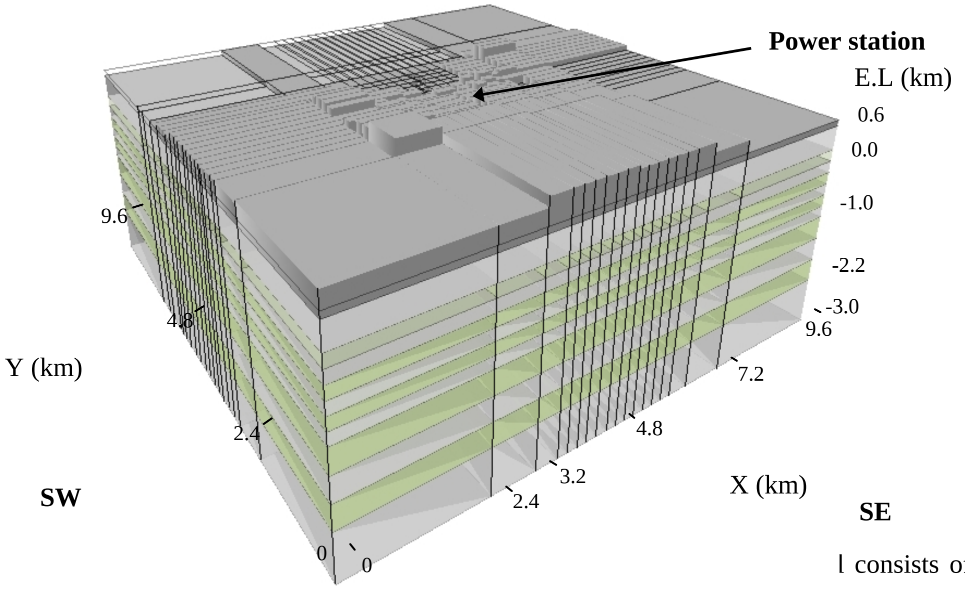
Inversion technique applied for numerical simulation can be defined as automatic calibration of a numerical model. A numerical simulator, iTOUGH2, is an optimization code that allows estimation of any input parameter of the nonisothermal, multiphase flow simulator TOUGH2 (Finterle et al., 1997). The iTOUGH2 code allows us to estimate TOUGH2 input parameters based on any type of observation for which a corresponding simulation output can be calculated. At the same time iTOUGH2 carries out a residual and error analysis that allows us to choose an optimum model. This simulator systematically modifies the values of a small set of parameters and uses mathematical optimization techniques to improve the match to the field data. The process requires a selection of parameters to be adjusted (i.e. to construct the objective function, Finsterle et al., 1999)

The iTOUGH2 allows us to simulate both natural state simulation and exploitation history. These simulations are carried out sequentially in a single run of iTOUGH2 (Finsterle, 2000). However, it may take a long computing time to attain optimum estimates of parameters with this method. In order to solve this problem, natural state simulation was conducted in this study, firstly. Then, both natural state and exploitation history was simulated sequentially using estimated parameters of natural state simulation as initial conditions.

3. NUMERICAL SIMULATION

3.1 Grid system

The code Mulgeom and Mulgraph (O'Sullivan and Bullivant, 1995) were used as pre-and postprocessor.



l consists of twelve

Fig. 2 Three-dimensional grid blocks for the numerical model of Takigami geothermal field.

A square area of 9.6 km by 9.6 km was selected for a grid system of numerical model with 3.0 km deep below sea level (b.s.l). Figure 2 shows three-dimensional blocks of the numerical model of Takigami geothermal field. The model consists of 4066 grids in a size range from 200 m by 200 m to 1.6 km by 1.6 km. In a vertical direction, the model was divided into 12 layers with different thickness ranging from 200 m to 800 m. The developed field for production and reinjection is located in the middle of the model with an area of 2.8 km by 2.4 km that consists of the grid with 200 m by 200 m. Main feed zone of wells are located in layers from -800 m to -1400 m b.s.l. Top layer represents the surface grid system. Elevation of the grid surface was given in a range from 600 m to 1200 m above sea level.

3.2 Rock properties

After the grid system of the model is developed, the next step is to divide the system into several zones on the basis of information on geology, reservoir boundary, and location of faults. Then, assignment of rock properties to each zone is required.

The rock properties consist of density, porosity, permeability, thermal conductivity and specific heat. Among them, permeability is the most important parameter that controls fluid flow in the geothermal system. Then, fourteen rock types were used on the basis of geological structure as noted in introduction.

Initial estimates of rock properties for numerical model are summarized in Table 1. Rock types are assigned to each grid to represent hydrogeological characteristics of subsurface formations.

layers as shown in Fig. 2. They are denoted as aa, bb, cc, dd, ee, ff, gg, hh, ii, jj, kk, ll, from the top surface to the bottom. Rock type feature is explained in detail as follows. All rock types are given the same values for density, porosity and specific heat as 2500 kg/m^3, 0.1 and 1000 J/kg/K, respectively. The rock type of NVL was assigned to aa and bb layers representing the Noine-dake volcanic rocks (Fig. 3). In the same way, the ALY and KSL rock types were assigned to cc and dd layers, respectively. The ALY represents Ajibaru formation and the KSL Kusu formation. The UTL and LTL represent Takigami formation, and then they were assigned in the western part of the model from dd to gg layer. The MED, MED1, MED2 and MED3 represent high permeable zone such as the Noine fault. The MAL was assigned to the layers from aa to cc corresponding to Mizuwake Andesite formation.

Table 1 Initial estimate of rock properties for the numerical model

Rock Type	Permeability (m^2) kx,ky	kz	Thermal Conduct. (W/(mK))
ATM	1.0×10^{-14}	1.0×10^{-14}	3.0
NVR	1.3×10^{-14}	1.0×10^{-12}	3.9
KLY	2.0×10^{-14}	1.6×10^{-15}	2.6
ALY	2.5×10^{-18}	5.0×10^{-20}	2.5
MED	6.3×10^{-14}	3.2×10^{-16}	3.6
MED1	1.1×10^{-12}	4.9×10^{-14}	1.3
MED2	4.0×10^{-15}	1.0×10^{-15}	1.3
MED3	7.7×10^{-15}	2.9×10^{-15}	2.1
UTL	1.3×10^{-15}	1.3×10^{-13}	1.5
LTL	1.0×10^{-13}	1.0×10^{-16}	2.3
MAL	1.0×10^{-14}	1.0×10^{-16}	4.0
UHW	2.0×10^{-12}	5.0×10^{-14}	1.8
UBAS	5.0×10^{-15}	1.0×10^{-15}	1.6
LBAS	1.0×10^{-13}	1.0×10^{-15}	2.1

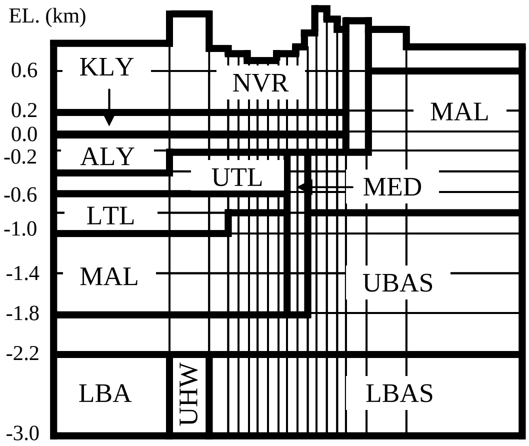


Fig. 3 Vertical slice at Y-4700 m and assignments of rock types.

The UBAS and LBAS represent basement of the system. Figure 3 shows a vertical slice at Y-4700m of the model that runs roughly through Wells TT-13 and NE-5 (see location Fig. 1 and 2).

4. CALIBRATION OF THE MODEL

4.1 Natural state simulation

The objective of natural state simulation is to reproduce the initial temperature and pressure distributions before any exploitation. The numerical simulations of the model should be carried out over a long time that allows the geothermal system to be equilibrated. This involves running the simulation until approximately steady conditions are obtained which takes a simulation period for about 1 million years. During the natural state simulation, the results were compared with the measured temperature profiles from 21 wells (135 data points). Parameters to be estimated are permeabilities of rock types, flow rates and enthalpies of recharges.

As for the initial conditions, all grids were filled with water of 15 °C and pressure equilibrated. Initial estimates of each rock properties are summarized in Table 1. Initial estimates of permeability were assigned to the model range from 5.0×10^{-20} to 1.1×10^{-12} m^2. The lowest value was given to the cap rock. The thermal conductivities were assigned in a range from 1.3 to 4.0 W/(mK).

For the boundary conditions, constant temperature and pressure of atmosphere were given as 15 °C and 0.879 bar at the top surface. Peripheries of the model were given to be impermeable to mass and adiabatic to heat except one grid that was assigned for fluid recharge. Mass recharges were assigned at two zones. In order to realize a recharge by lateral flow, Recharge A was assigned in the layer from -1000 to -1400 m b.s.l. at the most peripheral grid on the south east of the model. Another one was the west of bottom layer, Recharge B. Initial estimate of Recharge A was given with a flow rate of 5.0 kg/s and an enthalpy of 1250 kJ/kg. For Recharge B, 32.0 kg/s and 1250 kJ/kg were given. The heat fluxes of 0.08 W/m^2 were given to all grids of bottom layer.

4.2 Combined simulation

After performing a successful natural state simulation that matches well the temperature profiles of wells, estimated values of permeabilities and mass recharges were used as initial conditions for the subsequent simulations for a natural state in combination with exploitation stage. The main objective of this combined simulation is to develop a model that can simulate the observed data for about 11 years of exploitation from August 1996 to May 2007. Measured data to be matched include produced fluid enthalpies from five wells in addition to temperature profiles of 21 wells in the natural state. An objective function is defined as sum of the normalized residuals between measured and simulated values of the variables that measured. Produced fluid enthalpies from five wells were calculated using wellhead data that include wellhead pressure, steam and water flow rates. Data to be matched consist of 370-observation data set. Parameters to be estimated are permeabilities of rock types, flow rates and enthalpies of recharges.

As for initial conditions, all grids were filled with water of 15 °C and pressure equilibrated. Estimated values of permeabilities at the preceding natural state simulation were assigned to each rock types.

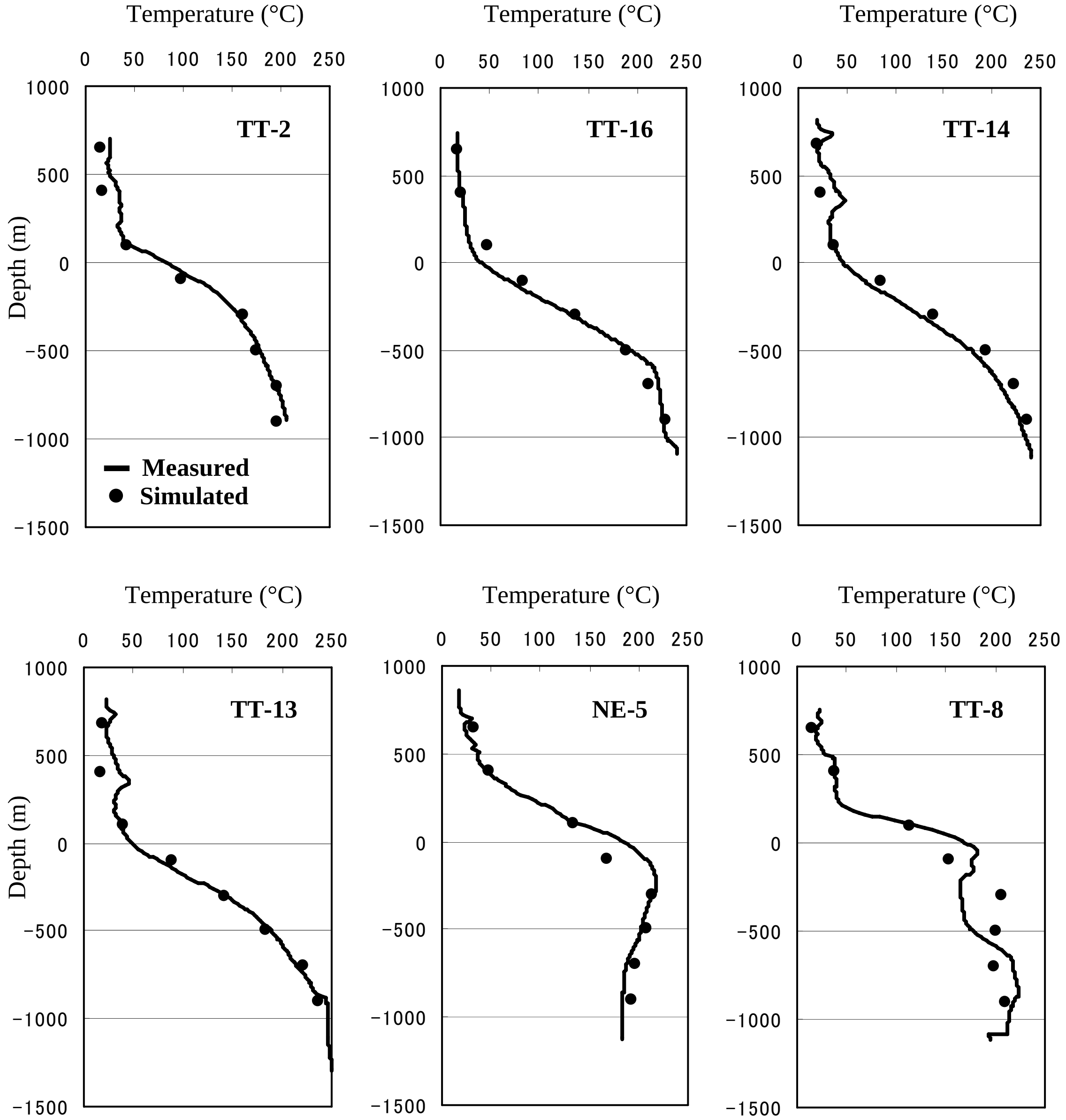


Fig. 5 Measured and simulated temperature profiles at main production zone of 6 wells TT-2, TT-16, TT-13, TT-14, NE-5 and TT-8.

For the boundary conditions, at the top surface, constant temperature and pressure of atmosphere were given as 15°C and 0.879 bar. Peripheries of the model were given to be impermeable to mass and adiabatic to heat except one grid that is assigned with Recharge A. Initial estimate of Recharge A was given a flow rate of 9.4 kg/s and an enthalpy of 995 kJ/kg. For the Recharge B, 47.6 kg/s and 1189 kJ/kg were given. The heat fluxes of 0.08 W/m^2 were given to all grids of bottom layer. Histories of production and reinjection flow rates were assigned as input data.

5. SIMULATION RESULTS

Figure 5 compares measured and simulated temperature profiles of six wells in natural state. The simulation was conducted using parameter values of the optimum model.

Relatively good match are observed for Well TT-2, TT-16, TT-13, and TT-14. Well NE-5 located to the east of Noine fault also shows a good match except at depth of -100 m b.s.l. Simulated temperature profiles of Well TT-8 show an isothermal distribution from -300 m to -900 m b.s.l. Because it is drilled across the Noine fault and located in the zone assigned with rock type MED. A model can successfully reproduce the temperature profiles of 13 wells in general.

Figure 6 shows a comparison of enthalpy measurements with simulated enthalpies for four production wells. Well TT-7 shows a reasonable match to measured enthalpy history. Measured enthalpies show slight increase with time and then decrease whereas simulated enthalpies show continuous decrease with time. In Well TT-8, simulated enthalpy shows lower values than those measured at early times. After the year of 2000, matches between two values are improved.

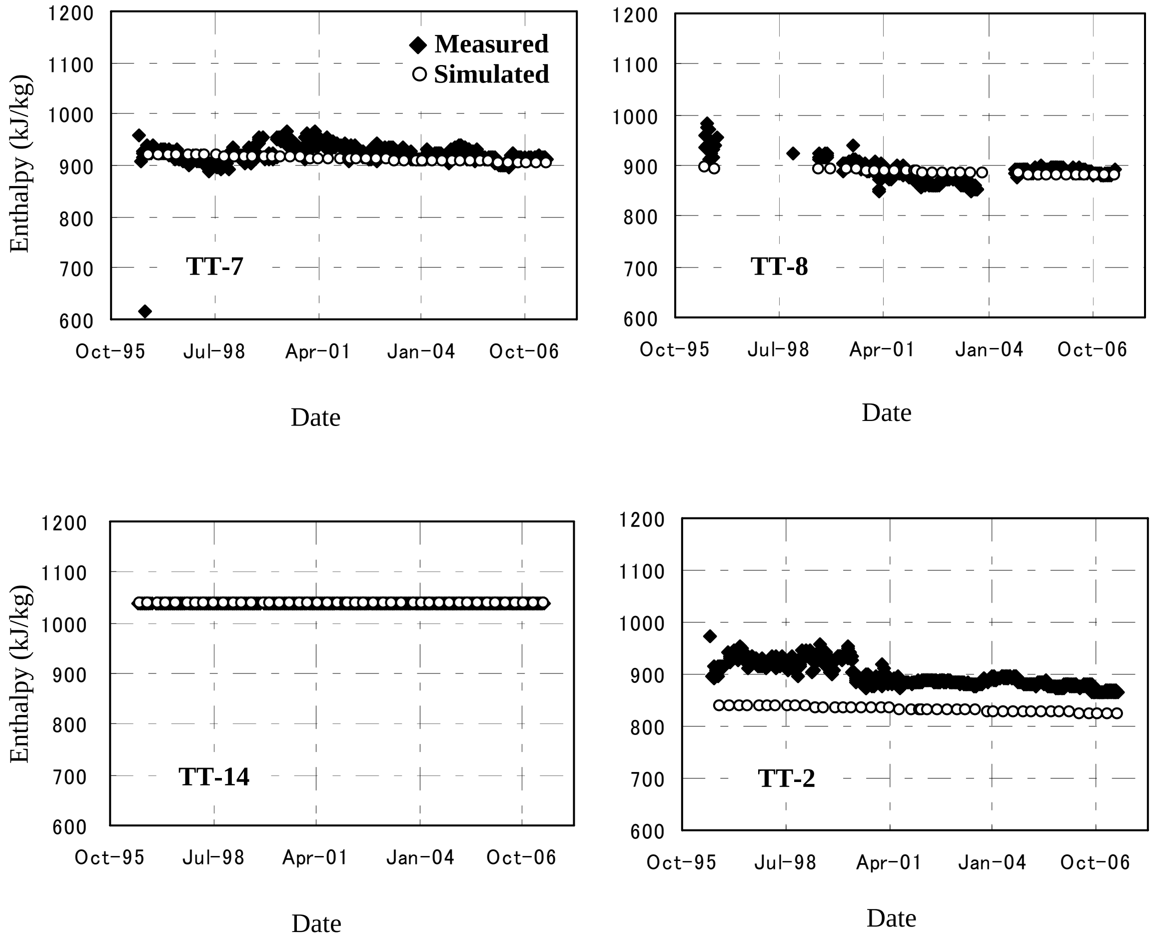


Fig. 6 Measured and simulated enthalpy histories of production wells TT-7, TT-8, TT-14 and TT-2

Good match in enthalpies are observed for TT-14 with the highest enthalpy of 1037 kJ/kg during most of the simulation period. Well TT-2 shows such that simulated enthalpies are lower than measured ones by 40-60 kJ/kg. These discrepancies can be attributed to the difference of temperature between measured and simulated at a feed point—layer from -800 m to -1000 m b.s.l— (Fig. 6). An enthalpy difference of saturated water between 205 °C (measured) and 196 °C (simulated) is 40 kJ/kg. In general, results exhibit a good match in four production wells.

Estimated permeabilities by the inverse analysis method are summarized in Table 2. Mass recharges assigned at Recharge A and B were estimated to be 11.4 kg/s of 875 kJ/kg and 50.2 kg/s of 1227 kJ/kg.

Table 2 Estimated permeabilities of each rock types

Rock Type	Permeability (m^2)	
	kx,ky	kz
ATM	1.00×10^{-14}	1.00×10^{-14}
NVR	1.57×10^{-14}	9.37×10^{-14}
KLY	3.43×10^{-15}	7.67×10^{-15}
ALY	2.51×10^{-18}	5.01×10^{-20}
MED	3.15×10^{-13}	6.86×10^{-14}
MED1	1.10×10^{-12}	4.90×10^{-14}
MED2	7.42×10^{-15}	2.78×10^{-16}
MED3	7.73×10^{-15}	2.86×10^{-15}
UTL	1.26×10^{-15}	1.26×10^{-13}
LTL	4.18×10^{-16}	5.70×10^{-16}
MAL	2.35×10^{-14}	2.30×10^{-16}
UHW	2.02×10^{-12}	5.01×10^{-14}
UBAS	1.00×10^{-15}	2.57×10^{-15}
LBAS	1.00×10^{-13}	1.00×10^{-15}

6. CONCLUSIONS

We have constructed a numerical model of the Takigami geothermal field by inverse analysis method. Parameters included in the model such as permeabilities, flow rates and enthalpies of recharges have been estimated. The results are summarized as follows:

1) A model can successfully reproduce the initial temperature profiles of 13 wells with natural state simulation.

2) The model provides a good overall match with measured enthalpies of four production wells except Well TT-2 at exploitation history.

3) Flow rates and enthalpies of recharge zones assigned at two different locations were estimated to be 11.4 kg/s of 875 kJ/kg and 50.2 kg/s of 1227 kJ/kg respectively.

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