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INVERSE MODELING OF THE EXPLOITATION OF THE MUTNOVSKY GEOTHERMAL FIELD 1984-2006

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ABSTRACT

The history of the exploitation of the Mutnovsky geothermal field includes multi-wells flowtests 1984-1987, a build-up period 1988-1998, followed by 12 MWe pilot PP start up in 1999, with a full-scale installed capacity of 62 MWe since 2002. An initial 3D rectangular TOUGH2 numerical model (Kiryukhin, 1996) was designed "as simple as possible" to contain a minimum number of elements (500+) to describe the existing production/injection wells and the reservoir. This model covers 5×5×2 km^3, includes 21 domains with different petrophysical properties, heat and mass recharge defined at the base layer, and discharge corresponding to known significant hot springs and steam ground areas. Preliminary recalibration of this model using 1984-2006 history exploitation data and inverse modeling capabilities of iTOUGH2-EOS1 was performed. Monthly averaged enthalpies of five production wells during the time period 1984-2006 are used for model calibration. Fractures permeabilities and porosities of the model elements containing these five production wells and reinjection rates of four wells were assigned as parameters to be estimated. A sensitivity analysis shows that the most influential parameters are reinjection rates, with estimates in range of 0-12% of reported values. Additional improvement of the model convergence was found after capillary pressure functions were assigned in two-phase model elements.

INTRODUCTION

Exploitation of the Mutnovsky geothermal field (Fig. 1) with installed power plants capacity of 62 MWe is important for Kamchatka renewable energy use. Besides, Mutnovsky experience may be useful in development projects of other large geothermal fields in Kamchatka-Kurile region to understand relationship between volcanic, hydrothermal and seismic activity. A large-scale exploitation started from 2000 year with fluid extraction up to 500 kg/s (600 MW) comparable with the energy rates of adjacent active volcanoes: Mutnovsky (8 km, 190 MW without fumaroles activity #1, 2, 3) and Gorely (10.5 km, 100 MW, without fumaroles activity #10). Field development is synchronized with seismic activity increase (KB GS RAS), hydrothermal explosions, emerging of new boiling pots (#6), and decline (Viluchinsky #18) or disappearance of hot springs adjacent to the exploitation area (Voinovsky #13 and Verkhne-Zhirovsky #14 hot springs) (Fig. 1). The process of the Mutnovsky field exploitation and related events need integrated hydrogeological analysis, including modeling study aiming at development of the new methods of exploration, geothermal resources and reserves assessment.

MODEL SETUP

An initial 3D rectangular TOUGH2 numerical model of the Mutnovsky geothermal field (Dachny site) was developed in Lawrence Berkeley National Laboratory in 1991 year on supercomputer CRAY-X-MP. Model calibration was performed by "trial and error" method at that time, nevertheless appropriate convergence with exploitation history 1984-1987 was achieved. This model application for different exploitation scenarios was discussed in papers (Kiryukhin, 1996, 2002). Models development tools have been significantly improved in recent years with effective TOUGH2 pre- and postprocessors and inverse modeling iTOUGH2 capabilities. Hence, the Mutnovsky model 1996 has been recently rebuild with preprocessor PetraSim v.5.0 (Fig. 2). Interest to this model is related to Mutnovsky geothermal field reserves estimation, since this model was designed "as simple as possible" to contain a minimum number of elements (500+) to describe the existing production/injection wells and the reservoir. Such model is referred to as a "hydraulic type model", which is acceptable by Russian Authorities for high temperature geothermal reservoirs reserves estimation.

This model with top at +750 m.a.s.l., covers 5×5×2 km^3, includes 5 horizontal layers and 500 basic grid elements of 500×500×500 м^3 each, 21 domains with

different petrophysical properties, heat and mass recharge defined at the base layer, and recharge corresponding to known significant hot springs and steam ground areas. In all elements of the base layer of the model a conduction heat flow 60 mW/m^2 was defined, in selected elements corresponding to upflow zones mass flows were assigned (39 kg/s, 1390 kJ/kg + 15 kg/s, 1270 kJ/kg), discharge conditions were specified in the model elements corresponding to Dachny and Verkhne-Mutnovsky steam fields, and Zhirovskoy river basin hot springs (15 kg/s). Twenty-two wells were defined in the model, including 18 production (016, 049N, 055, 048, 26, 24, 037, 1, 013, 014, 01, 045, 022, 029W, 4E, 017N, 053N, 042) and 4 groups of injection (027 (+028+044), 07, 043N, 054N (+024N)) wells. Production and injection wells were defined in the model with the time depending rates and enthalpies (for injection wells) in accordance with the reported data (Maltseva et al, 2007).

Double-porosity was assigned in the model elements containing slotted intervals of production/injection wells. Note, that double-porosity needs to reproduce excess enthalpies of the modeling production wells during exploitation. Wells 016, 26, 01, 1, 24 demonstrate enthalpies greater than enthalpy of liquid water at given temperature, pointed out on local boiling in the underground reservoir. Double porosity assignment in the model was achieved by reducing initial volume of the "fractured" model element and adjoining it to the low permeable "matrix" element with the volume equal to difference between initial volume and "fractured" element volume.

INPUT DATA FOR MODEL CALIBRATION AND MODEL PARAMETRIZATION

At the early stage of the Mutnovsky geothermal field exploitation in 1984-1988 years a long term multi well flow tests were performed. During that time the most reliable data were obtained from five production wells: 26, 016, 01, 1, 24 (Asaulov et al, 1989). Later, as a large-scale exploitation of the Verkhne-Mutnovsky (12 MWe, 2000 year) and Mutnovsky (50 MWe, 2002 year) started, the number of production wells was increased. By that time the most reliable data on transient rates and enthalpies were obtained from the following production wells: 26, 016, 1, 24, 4E, 013, 016, 017N, 029W, 037, 042, 048, 049N, 053N, 055 (Maltseva et al, 2007).

Hence, monthly averaged enthalpies of five production wells 26, 016, 01, 1, 24 during the time period 1984-2006 are used for model calibration, with the total number of observational points being 523. Use of the enthalpies as a main calibration parameter explained that this is a directly measured parameter, which reflects volumetric properties of production zones penetrated by wells. Standard enthalpy deviation is assumed to be less 100 kJ/kg.

Fractures permeabilities and porosities of the model elements containing five production wells above mentioned and the rates of four groups of injection wells (027 (+028+044), 07, 043N, 054N (+024N)) were assigned as parameters to be estimated (Table 1). Use of the reinjection rates as adjustable parameters was necessary due to the impossibility to reproduce enthalpies of the production wells at injected rates reported in (Maltseva et al, 2007).

MODELING RESULTS AND DISCUSSION

Direct TOUGH2-EOS1 (Pruess, et al) modeling with input data corresponding to 3D rectangular TOUGH2 numerical model (Kiryukhin, 1996) run show significant deviations of modeling enthalpies from observed data (Run #9). Standard deviation is accounted 693 kJ/kg, bias 375 kJ/kg (production wells 26, 016, 01, 1 and 24 enthalpies). Figs. 3 and 4 show that, that such non convergence of modeling and observed data was caused by unrealistic fast cooling in the model during 2000-2006 year time period.

Hence, inverse iTOUGH2-EOS1 modeling was used (Finsterle, 1999). In this study BETA version of iTOUGH2-EOS1 was used. Inverse modeling allows estimates of 13 parameters (Table 1) and improves convergence of the model with observational data (Run #EX-9). Standard deviation obtained is 442 kJ/kg, bias is 210 kJ/kg (production wells 26, 016, 01, 1 and 24 enthalpies) (Figs. 3 and 4). Estimated reservoir parameters updates are not very significant, except the fracture porosity decline in the well 016. Injection rates were found to be the most sensitive model parameters, their estimates are 0-38% of reported in (Maltseva et al, 2007). Nevertheless, it worth noting a strong correlation between estimated injection rates of the adjacent groups of wells (027 and 07, 043N and 054N), and that group (043N and 054N) is remotely located from model calibration points. Hence redistributions of injection rates estimates are possible. Modeling (Run #EX-9) shows significant extension of two-phase conditions in the reservoir by 2006 year at depth elevations from -250 to +250 m.a.s.l., pressure decline (from 63 to 10 bars) and temperature decline (from 280 to 180 ^oC) in local points of the central part of the production area.
Additional improvement of the model convergence was found after capillary pressure functions (linear, CP1=1 bar) were assigned in two-phase model matrix elements, containing production wells 016 and 26. This significantly improves convergence of the model with observational data (Run # 9A). Standard deviation obtained was 152 kJ/kg, bias was -59 kJ/kg (production wells 26, 016, 01, 1 and 24 enthalpies) (Figs. 3 and 4).

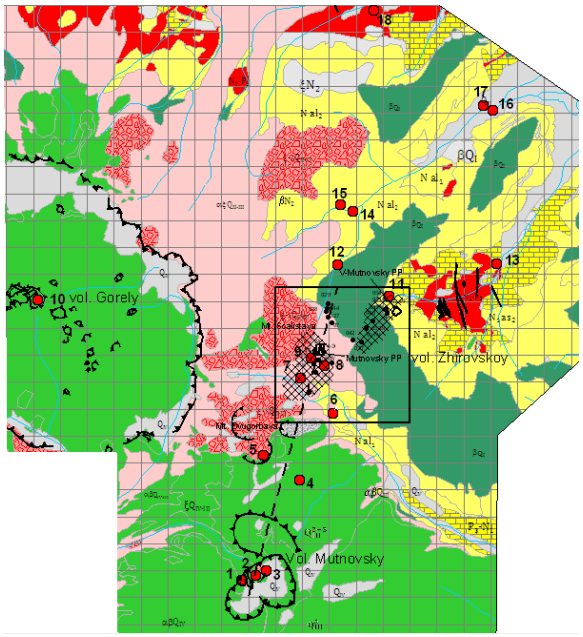

Figure 1: Schematic geological map of the Mutnovsky geothermal area. Rectangle – defines model limits; circles with numbers -wells; double circles – thermal discharge areas; a dashed line – horizontal projection (at 0 m.a.s.l.) of the Main production zone, hydraulically connecting volcanic and hydrothermal systems; crosses define a two-phase area at +250 m.a.s.l. (modeled by the end of 2006 years). Map grid – 1 km.

Table 1: Re-estimation of the model parameters based on iTOUGH2-EOS1 inversion with observational data of the Mutnovsky exploitation in 1984-2006 years.

Estimated parameters	Dimension	Run #9	Run #EX-9
K_{fra} (well 016)	mD	6	11.2
θ_{fra} (well 016)		0.20	0.00004
K_{fra} (well 26)	mD	9	6.0
θ_{fra} (well 26)		0.20	0.36
K_{fra} (well 01)	mD	1.5	1.2
K_{fra} (well 1)	mD	0.6	0.3
K_{fra} (well 24)	mD	4.5	7.6
Permeability (Layer2, TUFF2)	mD	2.9	3.7
Permeability (Layer3,SAND1)	mD	4.5	4.5
Injection rate (027+028+044)	%	100	38
Injection rate (well 07)	%	100	11
Injection rate (well 043N)	%	100	0
Injection rate (054N+024N)	%	100	0

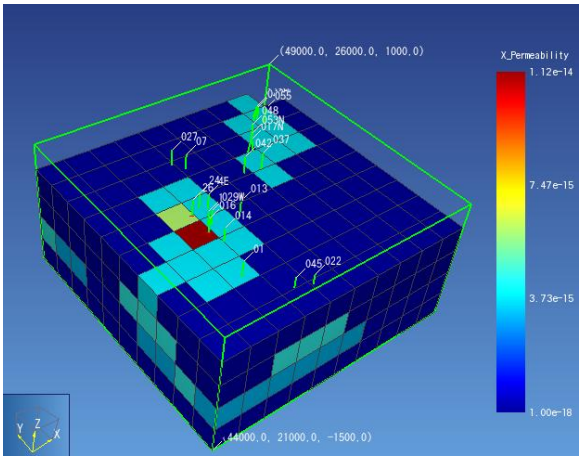

Figure 2: 3D rectangular model of the Mutnovsky geothermal reservoir (view from the top of the 2-nd layer, +500 m.a.s.l.). This figure shows the geometry of numerical grid and permeability distribution (m^2).

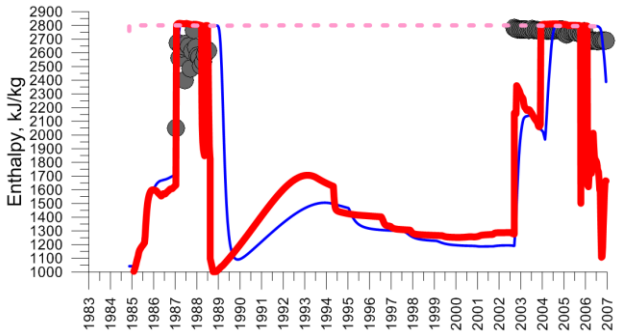

Figure 3 Matches of the observational monthly enthalpy change data and modeling data of the well 016 during the exploitation in 1984-2006 years. Filled circles are observational data, a thin line – direct TOUGH2 modeling (Run #9),a thick line – inverse iTOUGH2 modeling (Rune #EX-9), a dashed line is additional (Run #9A).

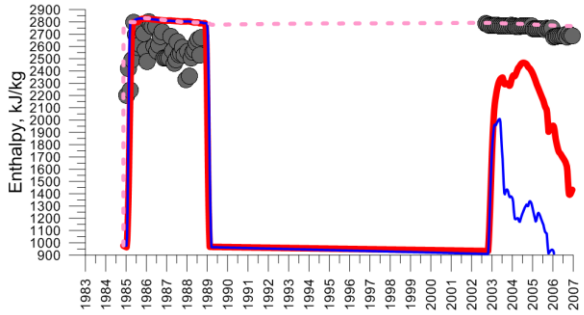

Figure 3 Matches of the observational monthly enthalpy change data and modeling data of the well 26 during the exploitation in 1984-2006 years. Filled circles are observational data, a thin line – direct TOUGH2 modeling (Run #9), a thick line – inverse iTOUGH2 modeling (Run #EX-9), a dash line is additional (Run #9A).

FUTURE PLANS

Model calibration will continue to improve convergence modeling and observational data. Installation of the double-porosity in all elements including production wells (4E, 013, 017N, 029W, 037, 042, 048, 049N, 053N, 055) will take place. Observational data base will be appended by temperature and pressure measurements during the exploitation period (including wells 30 and 012 operated with capillary tubing systems and other monitoring wells, where PT logging was performed), as well as production enthalpies datasets obtained after 2006 year. There is also possibility to use chloride change in fluids (production wells, adjacent hot springs) and gas composition (CO_2, N_2, CH_4, O_2) change (production wells) for additional model calibrations (for these purposes EOS1 with tracer and TMVOC correspondingly should be used). The number of estimated parameters will include parameters characterized by the cold water inflow zones into the production reservoir, dependence of the high temperature upflow rate on pressure drop in the reservoir. It is also suggested to apply the model for identification of the potential shallow hydrothermal explosion zones and evolving two-phase reservoirs.

There are also plans to create a regional model of the Mutnovsky area by extending the existing model to the limits of a geological map, shown on Fig. 1 (e.g. integration into the model Mutnovsky and Gorely active volcanoes and Zhirovaya river basin). This 21 x 23 x 4 km^3 model may require up to 16K grid elements (if 500 x 500 x 500 m^3 cells are used), which is supported by current computing and programming facilities. This regional model will help to understand influence of the Mutnovsky geothermal reservoir exploitation on adjacent active volcanoes and hot springs to avoid potential catastrophic events like Geysers Valley landslide of June 3, 2007 or trigger ignimbrites eruptions from Gorely and Mutnovsky volcanoes magma chambers.

CONCLUSIONS

3D rectangular model of the Mutnovsky geothermal field (Dachny site) (Kiryukhin, 1996) was rebuilt with preprocessor PetraSim v.5.0. Inverse BETA version of iTOUGH2-EOS1 modeling was used for preliminary model recalibration based on history of the exploitation in 1984-2006 years. Monthly averaged enthalpies of the five production wells were used as observational data. Multi parameter inversion modeling improves model convergence to observational data. Re-estimates of fracture permeabilities and porosities of the production wells and the reservoir were performed, and reinjection rates were found to be the most sensitive estimation parameters. Inverted estimates of the injected rates accounted to 0-38% of the data reported in (Maltseva et al, 2007). Additional improvement of the model convergence was found after capillary pressure functions were assigned in two-phase model matrix elements. The liquid phase trapped there promotes observed sustainability of steam production. Additional study to obtain better convergence between modeling and observational data is needed.

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