A 20 YEAR PROGRESS IN THE TOUGH2 MODELING OF THE MUTNOVSKY GEOTHERMAL FIELD, KAMCHATKA, RUSSIA

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ABSTRACT

An initial 3D, rectangular, 517-element (partially double-porosity) TOUGH2-EOS1 numerical model of the Mutnovsky geothermal field (Dachny site) was developed in 1992–1993. (Kiryukhin, 1996). This model calibration was performed by trial and error, with six temperature and three pressure data as key calibration points. Visual matches with temperature/pressure distributions maps were conducted for natural-state model calibration, and five wells providing enthalpy transient data were used for exploitation history in calibrating the years from 1984 to 1987. This simple model was used for the Mutnovsky geothermal project feasibility study, followed first by a 12 MWe pilot project started in 1999, and then a full-scale system with a capacity of 62 MWe, in operation since 2002.

The same geometric model has been recently adopted in rebuilding the preprocessor PetraSim v.5.0. Observational data used for model recalibration are as follows: 29 key temperature calibration points for the natural state, 14 production wells with monthly averaged enthalpies (592 values during the time periods 1983–1987 and 2000–2006), and two transient pressure monitoring wells (51 values from 1995 to 2006) for exploitation history match.

The recalibration process (started by hand) reveals necessity to add double porosity in all active permeable elements, increase reservoir permeabilities and improve boundary conditions. Second stage of recalibration using iTOUGH2-EOS1 inversion modeling capabilities, was very useful to remove outliers from calibration data, model parameterization and parameter estimation.

Comparison of the reservoir parameter estimations (which have been recently obtained using iTOUGH2 inversion modeling) with reservoir parameters (which were estimated by TOUGH2 “trial-and–error” method 20 years ago, given in parentheses) are as follows: total upflow recharge rate in natural conditions 80.5 (54.1) kg/s, Main upflow enthalpy 1430 (1390) kJ/kg, reservoir permeabilities based on history match 27-616 (3-90) mD. Inverse modeling was also used to estimate unknown parameters and boundary conditions attributed to exploitation: reinjection rates, meteoric downflow recharge in the central part of the geothermal field and reservoir compressibility, which add upflow component during exploitation.

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.

Since the beginning of large-scale exploitation, Mutnovsky field production experienced significant steam fraction decline from 0.46 to 0.27 during the first years (2002 – 2006) of the exploitation (Fig. 2). Some production wells were switched of exploitation (049N, 055, 5E, 4E, 053N, 017N) due to reasons which are not completely understood. There is also some evidence of the local meteoric water inflow in reservoir (Kiryukhin et al, 2010).

In adition, large-scale exploitation started from 2000 year with fluid extraction up to 500 kg/s (600 MW) comparable with the magma energy rates of adjacent active volcanoes: Mutnovsky (8 km, 190 MW) and Gorely (10.5 km, 100 MW).

Mutnovsky field development is synchronized with increased hydrothermal explosion activity of Mutnovsky volcano after 40 years of silence (hydrothermal explosions in crater on March, 17, 2000, April, 2007 and May, 2012) (Gavrilenko, 2008), initialization of fumaroles activity of Gorely volcano in 2010 and drainage of Mutnovsky crater lake (2004) and Gorely crater lake (2012). It is also noted by seismic activity increase (11 earthquakes Ks=4.1-5.4 recorded at depth from 2 to 6 km during the time period from Feb. 2009 to May 2012 (data of KB GS RAS)).

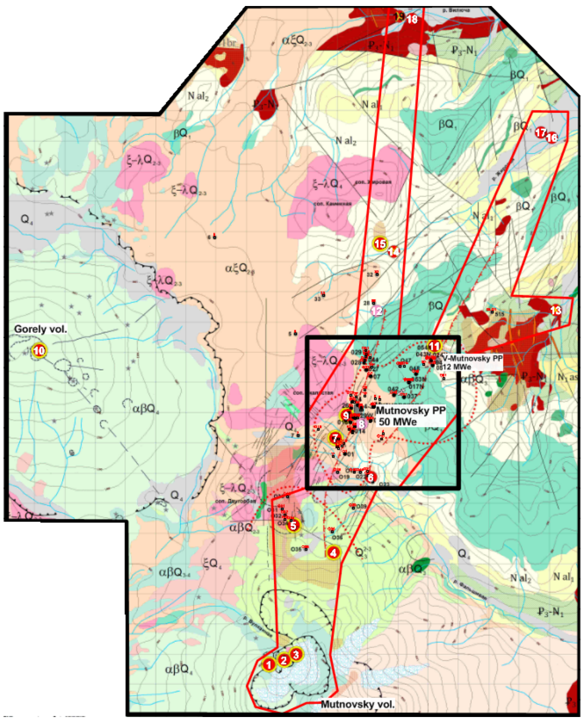

Figure 1. Schematic geological map of the Mutnovsky geothermal area. Black rectangle – defines model limits; circles with numbers - thermal sites (fumaroles or hot springs areas); a dashed line – horizontal projection (at 0 m.a.s.l.) of the Main production zone, hydraulically connecting volcanic and hydrothermal systems; red polygon – boundaries of the North Mutnovsky Volcano-Tectonic Zone; dotted line – temperature contour 230°C at -250 masl. Map grid – 1 km.

Hydrothermal explosions and emerging of new boiling pots (#6) inside the exploitation area, degradation of chloride hot springs in the areas, adjacent to geothermal field are noted (2 bars pressure decline at Viluchinsky Site (#18), disappearance of Voinovsky (#13) and Verkhne-Zhirovsky (#14) hot springs, significant chloride decline at Nizhne-Zhirovskoy hot springs are recorded (Fig. 1).

Hence, the process of the Mutnovsky field exploitation and related events need integrated hydrogeological analysis, including modeling studies targeting at development of the new methods of exploration, geothermal resources and reserves assessment, sustainability of the existing geothermal field and extension of its potential.

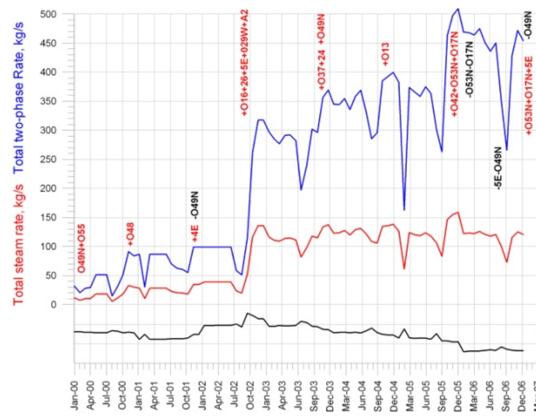

Figure 2. Mutnovsky geothermal field: observed total two-phase production rate (upper graph), observed total steam production rate (middle graph) and corresponding steam fraction (lower graph). Data from Maltseva et al, 2007.

MUTNOVSKY GEOTHERMAL FIELD MODEL SETUP

Model Setup

An “old” 3D rectangular TOUGH2 numerical model of the Mutnovsky geothermal field (Dachny site) was developed at Lawrence Berkeley National Laboratory in 1991 and simulated using the CRAY-X-MP supercomputer. Model calibration was achieved by “trial and error” to the 1984-1987 exploitation history. This model application for different exploitation scenarios was discussed in earlier papers (Kiryukhin, 1996, 2002).

Model development tools have been significantly improved in recent years with effective TOUGH2 pre- and postprocessors and inverse modeling (iTOUGH2) capabilities. Hence, the Mutnovsky 1996 model has been recently rebuilt with preprocessor PetraSim v.5.0

(Figs. 3-6). This model may also be applied 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 reservoir with production/injection. Such a model is referred to as a "hydraulic type model", which is acceptable by Russian Authorities for high temperature geothermal reservoir 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 conductive heat flow of 60 mW/m^2 was defined. In selected elements corresponding to upflow zones, mass flows were assigned (Main upflow: 39 kg/s, 1390 kJ/kg and NE upflow: 15 kg/s, 1270 kJ/kg) (Fig. 3).

Discharge conditions were specified in the model elements corresponding to the Dachny (D) and Verkhne-Mutnovsky (VM) steam fields, and integrated hot springs discharge (NZ) (Fig. 4). Integrated hot springs discharge (NZ) represents in the model all existing groups of hot springs in the areas adjacent to Mutnovsky geothermal field (see Fig.1, Nizhne-Zhirovsky, Verkhne-Zhirovsky, Viluchinsky) in a lumped parameter form.

Twenty wells were defined in the model, including 16 production and 4 groups of injection wells (027 (+028+044), 07, 043N, 054N (+024N)) wells (Figs. 4 – 6).

Production wells 016 and 26 are steam-dominated wells fed from the second layer from the top of the model (rhyolitic tuff layer, domain "Tuff2" in the model) (Fig. 4).

Production wells 01, 014, 029W, 24, 055, 048 and injection wells 027 (+028+044), 07 are located in the middle layer of the model, comprising volcanogenic and sedimentary rocks (domain "Sand1" in the model) (Fig.5).

Production wells 1, 4E, 013, 042, 037, 053N, 017N, 049N and injection wells 043N, 054N are located in the forth layer from the top of the model (intrusion contact zone, domain "Cont1" in the model) (Fig. 6).

Production and injection wells were defined in the model with the time-dependent rates and enthalpies (for injection wells) in accordance with the reported data (Maltseva et al., 2007).

Double-porosity was assigned in the old model defined in selected elements containing production wells to reproduce excess enthalpies of the modeling production wells during exploitation. Wells 016, 26, 01, 1, 24 demonstrate enthalpies greater than the 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.

<u>Some Modifications of the Old Mutnovsky Model</u>

Some direct runs of the Mutnovsky model with "old" parameters reveal, that reservoir permeability and fracture volume fractions should be increased to reproduce the long term history of exploitation. Some enthalpy increase in NE upflow up to 1350 kJ/kg was assumed. The enthalpy of upflows is believed to be estimated by maximum values of Na-K geothermometers for Mutnovsky geothermal reservoir (306-310^{o}C, that corresponds 1390 kJ/kg for water phase). Insignificant shift of NE upflow zone in SW direction was assumed too.

Global definition of the double porosity was assigned in the updated model, to be able to perform iTOUGH inverse modeling calibration, since "domain by domain" double porosity MINC processing is not available in current version of TOUGH2/iTOUGH2.

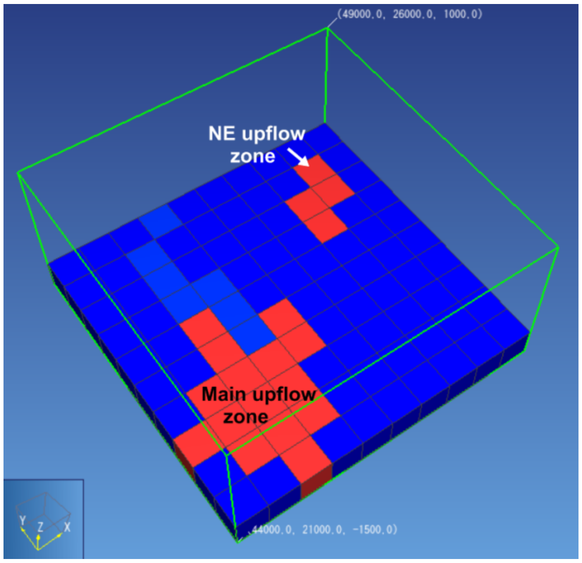

Figure 3. Base layer (-1250 masl) of the Mutnovsky geothermal field model. Upflow zones (Main and North-East (NE)) are shown by red color.

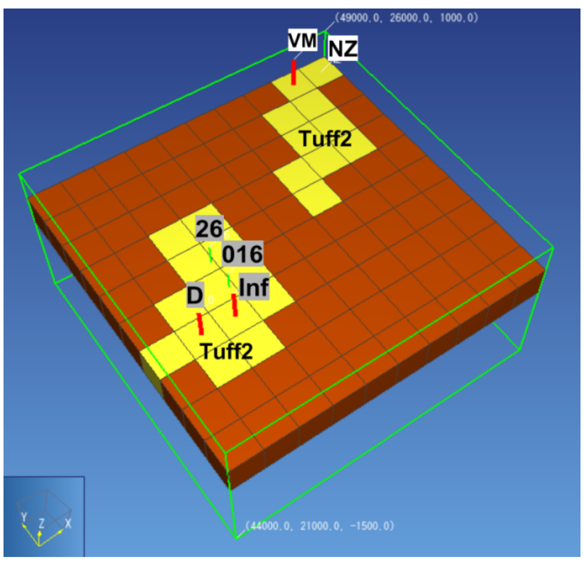

Figure 4. Layer +250 masl (2nd from the top) of the Mutnovsky geothermal field model. Positions of discharge elements of the model: D – Dachny fumaroles field (assigned in the top layer at +750 masl), VM – Verkhne-Mutnovsky fumaroles field (assigned in the top layer at +750 masl), NZ – integrated hot springs discharge area (assigned at +250 masl). Permeable reservoir domain "Tuff2", representing rhyolitic tuffs is shown by yellow color. Production wells 016 and 26 penetrated in this layer are shown by numbers on a grey background.

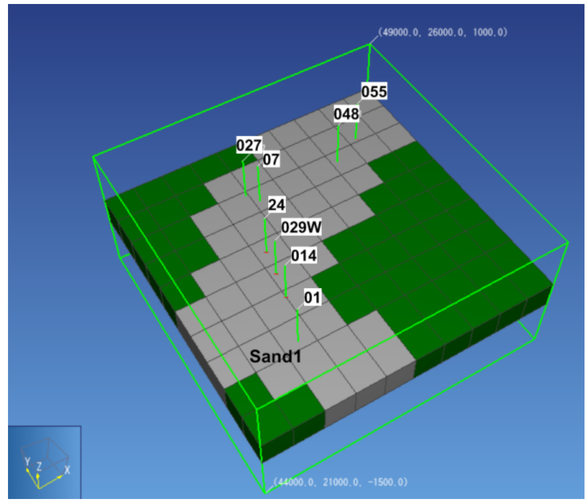

Figure 5. Layer -250 masl (middle) of the Mutnovsky geothermal field model. Permeable reservoir domain "Sand1", representing volcanogenic-sedimentary unit is shown by grey color, production wells penetrated in this layer are shown by numbers on a white background.

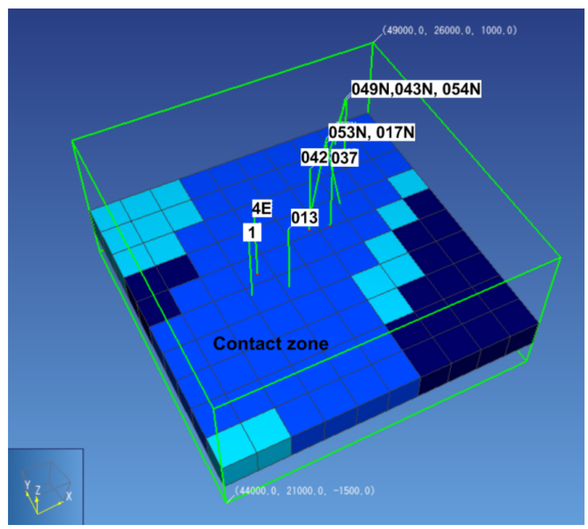

Figure 6. Layer -750 masl (2-nd from the bottom) of the Mutnovsky geothermal field model. Permeable reservoir domain "Cont1", representing intrusion contact zone is shown by blue color, production wells penetrated in this layer are shown by numbers on a white background.

NATURAL STATE + HISTORY EXPLOITATION iTOUGH2-EOS1 INVERSION MODELING

This study is aiming to use all available observational data (natural state temperatures and exploitation history data, including production wells transient enthalpies and monitoring wells transient pressures) for a single calibration modeling process. In order to do this, inversion modeling was organized so, that at the 1st stage natural state modeling runs from -∞ matching initially observed temperatures, then at the 2-nd stage modeling time is reset to 1985 year starting history match until 2006 year with production wells enthalpies and monitoring wells pressures as calibration data.

Observational data

Eight temperature measurements in wells confirmed by geochemical data (Na-K geothermometer) were selected for model calibration (natural state) and shifted into centers of model elements (Table 1). STD for temperature calibration data were assumed as 3ºC. Pressure data obtained from water column calculations during drilling are not to be used for inverse modeling calibration, since there is no guaranty that water levels are in equilibrium with two phase reservoir pressures due to significant circulation losses or skin effects at those wells.

Table 1. *Natural state temperatures used for model calibration (input data from Kiryukhin, 1996).*

Well	T Na-K, °C (geothermometer estimate)	T,°C (measured)	Model elevation, masl	Assumed calibration temperature, °C
016	Steam well	228	+250	228
26	Steam well	236	+250	236
01	298-310	275	-250	275
1	275-285	276	-250	280
24	276	265	-250	270
013	301-306	305	-750	304
037	282-298	284	-750	290
055	284		-250	284

Two pressure-monitoring wells #30 and #012 were used for exploitation history match. In those wells Pruett capillary tubing systems were deployed and pressure records available during the time period of 1995-2006 years (total number of 51 used pressure values). Capillary tubing chambers are located at -156 masl in well #30 and at -682.5 masl in well 012, hence pressure records were converted at elevations -250 masl and -750 masl to be consistent with the model grid. For these purposes, hydrostatic corrections for water column in well #012 were applied, while these corrections were not applied to well #30 at two phase conditions. STD for pressure calibration data were assumed as 1.0 bars.

14 production wells (016, 26, 01, 1, 24, 048, 042, 029W, 037, 013, 055, 049N, 4E, 017N) with monthly averaged enthalpies (592 values during the time period 1984-1987, 2000-2006 years) were also used for model calibration (Maltseva et al, 2007). It is worth noting, that regular production well testing usually took place just once in a year using a transportable full scale separator device C-100. The rest of the time, flow rates and enthalpies of production wells were defined as a function of WHP, based on annual flow test data. Additional control of the individual well flowrate and enthalpy (wells 016, 26, 01, 1, 24, 042, 029W, 037, 013, 4E, 017N) was achieved at Mutnovsky Power Plant (where total steam and water flow rates are recorded) when such well was closed, while other wells continue to produce. STD for enthalpy measurements data assumed 50 kJ/kg.

Estimated parameters

The list of estimation parameters is shown in Table 2.

Mass high temperature upflow rates.

There are two upflow zones identified in Mutnovsky field, since mass sources in each of these two zones were qualified as estimated parameters. Main Upflow includes 15 model elements, while NE-upflow includes 4 model elements, where mass sources were estimated.

Reinjection rates.

The rates of four groups of injection wells (027 (+028+044), 07, 043N, 054N (+024N)) were assigned as parameters to be estimated. Using the reinjection rates as estimated parameters was necessary due to the impossibility to reproduce enthalpies of the production wells at injected rates reported as 100% of production rate (Maltseva et al, 2007). Moreover, significant waste fluid discharge into the Falshivaya river and Trudny creek was clearly observed all the time of the Mutnovsky geothermal field large scale exploitation. Initial guess – 100%.

Fracturs permeabilities

Fracture permeabilities of the main reservoir geological units include values (from top to bottom) of: rhyolite tuffs (domain Tuff2), sandstones (domain Sand1), intrusion contact zone (domain Cont1), and diorite intrusion (MagmF). Initial guesses, respectively, are: 24 mD, 100 mD, 500 mD, 0.3 mD.

Natural discharge (productivity indexes)

There are three main discharge areas of the Mutnovsky geothermal field: Dachny (D) (steam), Verkhne-Mutnovsky (VM) (steam) and hot water discharge, represented by several groups of hot springs, but lamped in this model as "Nizhne-Zhirovskoy" (NZ) hot spring discharge (Fig. 2). All of these three discharge features are represented in the model like "wells on deliverability", with production indexes used as estimated parameter. In this case, "bottomhole pressures" were assigned as 15 bars (D, +750 masl), 5 bars (NM, +500 masl), 1 bar (NZ, +250 masl). Initial guesses for PI's are: 6.1E-10, 5.6E-12, 4.5E-12 m^3.

Infiltration rate

There is geochemical evidence of local meteoric water downflow into the production reservoir. The recharge area may coincide with the artificial Utinoe Lake and also some recharge may take place through damaged casings of the numerous old exploration wells, drilled in the Dachny Site Mutnovsky geothermal field in 80-th. Hence, one element of the top layer was assigned with the source of 42 kJ/kg injected water (local meteoric inflow), where mass flow rate was used as an estimated parameter of 154 kg/s (Fig. 3).

Double porosity parameters

Fracture spacing and fracture fraction porosity were used as estimated parameters. The double porosity approach was applied to all active elements of the model, hence these parameters are characterized with reservoir properties as a whole. The initial conceptual model for the double porosity approach is a 3D orthogonal fracture system with fracture fraction (FF) of 0.01 and fracture spacing (FS) of 50 m.

Rock compressibility

In spite of two-phase nature and significant boiling at shallow layers, lower parts of reservoir may contribute to some fluids due to compressibility. Hence, integrated compressibility of sandstones and the contact zone are considered as a model estimated parameter, with an initial guess of 1E-7 Pa^{-1}.

Discussion of the modeling results, estimates and convergence achieved

Table 2 represents five outputs of iTOUGH2-EOS1 modeling (scenarios #12-NS+EX-11, 7, 8, 11A, 12). Scenario 11 estimates reinjection flow rates as 42-85% of reported values at different reinjection sites (62% of total volume). If no reinjection is assumed at all, then objective functions significantly improve (scenarios 7, 8, 11A, 12). The minimum objective function (OF=11390) achieved corresponds to scenario 12.

Nevertheless, significant model standard deviations (STD) of temperatures (6.2^{o}C), pressures (1.9 bars) and enthalpies (179 kJ/kg) have been obtained in this modeling scenario. These modeling STD exceed corresponding measurements STD. Moreover, systematic underestimation of enthalpies (MEAN=71 kJ/kg) and temperatures (MEAN=14.9^{o}C), and systematic overestimation of pressures (MEAN=-0.9 bars) has been observed (Table 2).

This situation has been partially improved by adjusting one of relatively unknown parameters in the model: bottom hole pressure in discharge element D. This parameter is not included in the list of iTOUGH2 estimated parameters, hence we just change this to 25 bars by hand (scenario 12A, Table 2). This results in a significant decrease of the objective function (OF=7968) and systematic deviation of temperatures (7.4^{o}C) have been achieved.

Hence, the following estimations of the reservoir parameters for the best modeling scenario (#12NS-EX-12A) have been obtained (Table 2): Main upflow rate 60.2 kg/s, NE upflow rate 20.3 kg/s, tuffs permeability 27 mD, sandstones permeability 85 mD, contact zone permeability 616 mD, fractures spacing 4.3 m, fracture fraction porosity 0.42, infiltration rate 103 kg/s, thermal discharge area productivity indexes 1.1E-9 m^3, 5.9E-12 m^3, 6.6E-12 m^3 (for NZ, D and VM correspondingly), rock compressibility of sandstones and contact zone 1.3E-7 Pa^{-1}.

Table 2. Output of iTOUGH2-EOS1 inversion modeling (natural state+exploitation history): obtained values of estimated parameters and convergence achieved.

Estimated parameters	Dimension	Run ##12-NS+EX						
		11	7	8	11A	12	12A	6
Mass upflow (Main)	kg/s	3.66 x 15 =54.9	3.73 x 15 =56.0	3.83 x 15 =57.5	3.96 x 15 =59.4	3.76 x 15 =56.4	4.01 x 15 =60.2	
Enthalpy (Main)	kJ/kg							1432
Mass upflow (NE)	kg/s	3.81 x 4 =15.2	3.61 x 4 =14.4	3.44 x 4 =13.8	3.44 x 4 =13.8	3.52 x 4 =14.1	5.07 x 4 =20.3	
Enthalpy (NE)	kJ/kg							1406
Injection 027	%	53						
Injection 07	%	42						
Injection 043N	%	85						
Injection 054N	%	68						
Permeability Tuff2	mD	31	38	33	36	31	27	
Permeability Sand1	mD	114	98	96	89	83	85	
Permeability Contact zone	mD	307	745	750	789	631	616	
Permeability MagmF	mD	1.1	1.1					
Infiltration rate	kg/s	148		159	146	156	103	78
Fracture spacing	m			57	57	50	4.3	4.5
Fracture porosity				0.44	0.42	0.30	0.42	0.36
Prod. index NZ	m^3				2.9E-9	2.5E-9	1.1E-9	
Prod. index D	m^3				5.7E-12	4.3E-12	6.6E-12	
Prod. index VM	m^3				9.8E-12	5.2E-12	6.6E-12	
Compressibility Contact zone + Sand1	Pa^{-1}					4.3E-9	1.4E-7	1.4E-7
Convergence parameters								
Objective Function (OF)		13440	11640	11930	11440	11390	7968	10150
STD Temperature	°C	6.9	6.5	6.3	6.1	6.2	10.0	22.5
Mean Temperature	°C	16.2	16.2	15.6	15.4	14.9	10.5	-7.8
STD Pressure	bars	1.4	1.6	1.7	1.7	1.9	1.3	1.2
Mean Pressure	bars	-1.1	-1.1	-1.4	-1.6	-0.9	-0.9	-0.8
STD Enthalpy	kJ/kg	183	181	181	180	179	172	173
Mean Enthalpy	kJ/kg	80	80	78	76	71	51	45

Model Verification Using Direct Temperature and Water Level Measurements

Temperature logging performed during the exploration stage of Mutnovsky geothermal field during well drilling yielded 72 records of the bottom hole recovered temperatures. 29 of 72 measurements, which were closer than 250 m to the model element centers, were selected as additional calibration points for the natural state.

A direct iTOUGH2 run with parameters (#12NS-EX-12B) shows systematic underestimation of the temperatures (MEAN=7.5°C). This 7.5°C temperature model underestimation may be caused by Na-K geothermometer underestimation used to define the high temperature upflow base temperature (308°C).

Hence additional inversion modeling was performed with enthalpies of upflows used as estimated parameters with upper allowed limit of 1450 kJ/kg (318°C). Inverse modeling run #14-NS-EX-6 (this is 6-parameter run with the rest of parameters assigned accordingly to run #12, Table 2) updated the following estimates: Main upflow enthalpy 1432 kJ/kg (water 314°C), NE upflow enthalpy 1406 kJ/kg (water 311°C), fractures spacing 4.5 m, fracture fraction porosity 0.36, infiltration rate 78 kg/s, rock compressibility of sandstones and contact zone 1.4E-7 Pa^{-1}. Opposite to previous runs, this modeling scenario shows overestimation of temperatures (MEAN=-7.9°C), which is qualified as reasonable, caused by not full recovery of bottomhole temperatures.

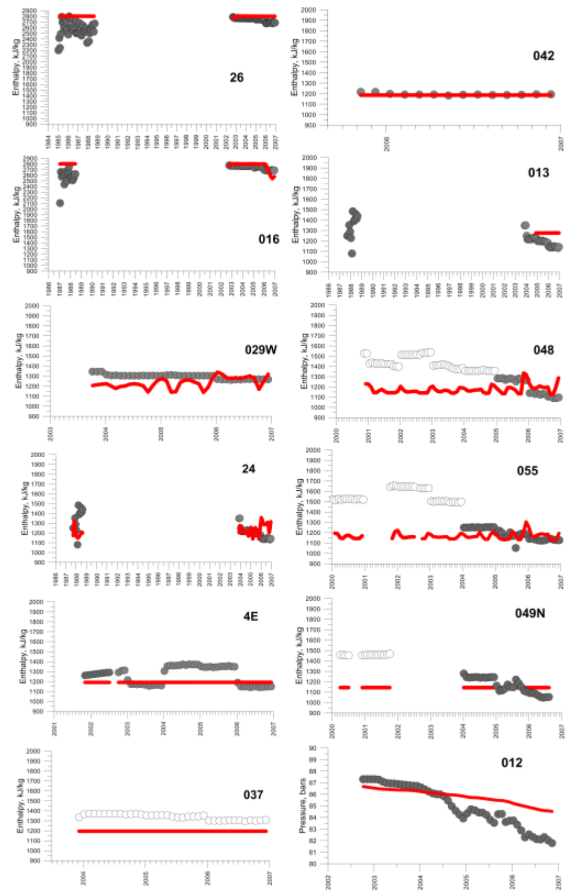

Figure 7. Transient enthalpy and pressure matches: grey circles – observational data, empty circles – potential outliers, red thick lines – modeling results (scenario #12-NS-EX-6).

Fig. 7 shows matches of this modeling scenario to observational data. As seen from Fig. 7, the model matches relatively well production enthalpies of wells from central part of the Mutnovsky geothermal field, including wells 26, 016, 24, 029W, 4E, 013, 042 (connected to Mutnovsky PP, where individual wells input may be confirmed). The largest enthalpy misfit occurs in wells 048, 055, 049N (connected to Verkhne-Mutnovsky PP), which were tested rarely using a transportable separator only. Hence, at this stage it is not clear whether additional model improvement, or data verification (for NE wells enthalpies) are needed.

Model (scenario #12-NS-EX-6) verification match with pressures calculated from water levels elevations in 11 wells was also performed (direct run). The match shows convergence in mean terms (MEAN= 0.3 bars), assumed to be reasonable taking into account the uncertainty of pressures calculated from water levels under high temperature reservoir conditions.

CONCLUSIONS

A TOUGH2-EOS1 numerical model of the Mutnovsky geothermal field (Kiryukhin, 1996) was re-calibrated using natural state and history exploitation data during the time period 1984-2006. Recalibration process (started by hand) reveals the necessity to add double porosity in all active permeable elements, increase reservoir permeabilities and improve boundary conditions. The second stage of recalibration using iTOUGH2-EOS1 inversion modeling was very useful to remove outliers from calibration data, identify sets of the estimated parameters of the model, and perform estimations.

The following features of Mutnovsky geothermal reservoir based on integrated analysis of natural state and exploitation data are now better understood: 1. Reservoir permeability was found to be one order more compared to the 1996 model, especially the lower part coinciding with the intrusion contact zone (600-800 mD at -750 - -1250 masl); 2. Local meteoric inflow in the central part of the field accounting for more than 80 kg/s since year 2002; 3. Reinjection rates are significantly lower, than officially reported at 100% of total fluid withdrawal (Maltseva et al, 2007); 4. Upflow fluid flows were estimated hotter (314^{o}C) and the rates are larger (+50%), than assumed before; 5. Global double porosity parameter estimates are: fracture spacing - 5 m, void fraction N 10^{-3}.

“As simple as possible” model yields reasonable convergence with production enthalpies (reflecting volumetric reservoir properties). We understand that the coarse model is not able to describe satisfactorily (with small deviations) point type measurements, such as bottom hole temperature records, etc. Nevertheless, large sets of such calibration data may improve model mean and forecasting properties.

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