MODELING AND OBSERVATIONS OF THE ENTHALPY, PRESSURE, CHLORIDE, CO₂ AND VERTICAL DEFORMATION TRANSIENT CHANGE IN THE MUTNOVSKY GEOTHERMAL FIELD (KAMCHATKA, RUSSIA)

A.V. Kiryukhin, O.O. Miroshnik, M.A. Maguskin, I.F. Delemen

Institute of Volcanology & Seismology FEB RAS
Piip-9
Petropavlovsk Kamchatsky, 683006, Russia
e-mail: AVKiryukhin2@mail.ru

ABSTRACT

A TOUGH2-EOS1 3D rectangular numerical model of the Mutnovsky geothermal field (Kiryukhin, 1996) was calibrated recently using natural state and history exploitation enthalpy and pressure data during the time period 1984-2006 years (Kiryukhin et al., 2012) was verified based on available additional data on transient steam production rate 2007-2009 years, chloride and non condensable gas in production wells and chloride hot spring, reservoir pressure, and earth surface vertical deformations data. In particular iTOUGH2 with different modules (EOS1, EOS1+tracer, EOS2) was used as a tool for this verification.

Direct modeling shows total steam production rate reasonably matches Mutnovsky data in 2007-2008. Transient chloride and non condensable gas (CO₂) inversions confirm existing model parameters (fracture spacing, fracture porosity, downflows) and additionally yield the estimates for chloride (120-144 ppm) and CO₂ (180 ppm) mass fractions in high temperature upflows zones. Model properties qualitatively match positive vertical surface deformations (up to 5 mm/year) observed in steam dominated area, and subsidence (up to 18 mm/year) observed in liquid dominated production reservoir.

INTRODUCTION

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 years (Kiryukhin, 1996). This model calibration was performed by handle “trial and error” method at that time, 5 wells enthalpy transient data were used for exploitation history in 1984-1987 years calibration. Nevertheless, this simple model was used for Mutnovsky project feasibility study, followed by 12 MWe pilot PP started up in 1999, with a full-scale installed capacity of 62 MWe since 2002.

The same geometry model has been recently recalibrated based on the exploitation history match (1984-2006 years) (Kiryukhin et al., 2012). Recalibration using iTOUGH2-EOS1 inversion modeling capabilities, was useful to remove outliers from calibration data, identify sets of the estimated parameters of the model, and perform estimations. Comparison of the reservoir parameters 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) is 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 the exploitation: reinjection rates, meteoric downflow recharge in the central part of the geothermal field and reservoir compressibility.

In this study we do verification of the model above, matching with the available additional data transient total steam production rate, reservoir pressure, chloride and CO₂ changes in production and monitoring wells, chloride hot spring of the Mutnovsky geothermal area, as well as with surface vertical deformation data spanning time interval until 2012 year. Model geometry is also discussed.

MUTNOVSKY GEOLOGICAL SETTING & MODEL GEOMETRY

Mutnovsky geothermal field is located in North-Mutnovsky volcano-tectonic (NMVT) zone, which was created by radial fracturing originated from...
magmatic systems of Mutnovsky volcano (located 8 km apart) and Gorely volcano (located 10.5 km apart), as well as local magmatic intrusions inside (Fig. 1).

Figure 1: Schematic geological map of the Mutnovsky geothermal area. Red polygon – boundary of NMVT zone; black rectangle – defines model limits; circles with numbers - thermal sites (fumaroles or hot springs areas); a thick red lines – horizontal projections (at 0 m.a.s.l.) of the Main production zone, hydraulically connecting volcanic and hydrothermal systems and NE production zone; dotted line – temperature contour 230°C at -250 masl. Map grid – 1 km.

NMVT zone is clearly defined by hot springs and fumaroles fields distributions, upper Pleistocene rhyolite domes occurrences (Fig. 1) and includes three segments of different strike: S-NNE, S-NE and WE. S-NNE segment of NMVT zone is traced by fumaroles fields of Mutnovsky volcano crater (1, 2, 3), North-Mutnovsky West fumaroles (5), Dachny, Medvji fumaroles (5, 7, 9), Piratovsky condensate spring (12), V-Zhirovsky fumaroles (15) and chloride hot springs (14), Vilyuchinsky chloride hot springs (18, 19). NNE segment is also included Main Production Zone, which supplied significant fraction of steam to Mutnovsky PP 50 MWe. S-NE segment includes North-Mutnovsky East fumaroles (4), Verkhne-Mutnovsky fumaroles (11) and Nizhne-Zhirovsky chloride hot springs (16, 17). WE segment seems to be derived from Gorely volcano radial fracture zone and includes Voinovsky chloride hot springs (#13).

Geological cross sections of NMVT zone are shown on Fig.2 are demonstrated the following features of production geothermal field and adjacent thermal and volcanic features: 1. Production occurs mainly from Main and NE fault type production reservoirs, as well as from top of Miocene volcanogenic-sedimentary units, either intruded by diorites (intrusion contact zone) or adjacent to permeable contact between N-Q, Nal volcanogenic basin and P3-N1 basement rocks; 2. Production reservoirs are hydraulically connected to Mutnovsky volcano and adjacent chloride hot springs (14, 16, 17, 18, 19) through NMVT zone. There is a possibility of hydraulic connection of production reservoirs and Gorely volcano too.

3D rectangular model (Kiryukhin et al, 2012) applied to Mutnovsky reservoir exploitation history calibration is significantly smaller, than NMVT zone (this model is shown as rectangle on Figs.1 and 2). Nevertheless, this model can be used as a basic model until more complicated models be verified. Natural chloride springs discharge in this basic model...
is lumped in one model element NZ, corresponding to total chloride discharge ((14, 16, 17, 18, 19) to match model with observational data.

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, VM – Verkhne-Mutnovsky fumaroles, NZ – integrated hot springs discharge area. Permeable reservoir domain “Tuff2”, representing rhyolite tuffs is shown by yellow color. Production wells 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 (2nd 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.

TRANSIENT STEAM PRODUCTION RATE & RESERVOIR PRESSURE MATCH

In the previous study 13 production wells with monthly averaged enthalpies (650 values during the time period 1983-1987, 2000-2006 years) and 1 transient pressure monitoring wells (57 values during 2003-2006 years) were used for exploitation history match (Fig.7 and 8) using iTOUGH2-EOS1
At that time the best inversion parameters set (#12NSEX6) yield standard enthalpy deviation STD=173 kJ/kg with mean bias MEAN=45 kJ/kg, and reservoir pressure STD=1.2 bars with MEAN=-0.8 bars.

The following features of Mutnovsky geothermal reservoir based on integrated inverse modeling analysis of the natural state and exploitation data were estimated and better understood (Kiryukhin et al, 2012): 1. Reservoir permeability was found to be one order more comparable to model-1996, especially the lower part coinciding with intrusion contact zone (600-800 mD at -500 - -1000 masl), reservoir compressibility - 1.47 $10^{-7}$ Pa$^{-1}$ (at 0 - -1000 masl); 2. Local meteoric inflow in the central part of the field accounting for 45 - 80 kg/s since year 2002; 3. Reinjection rates were estimated significantly lower, than officially reported as 100% of total fluid withdrawal; 4. Upflow fluid flows were estimated hotter (314 oC) and the rates are larger (+50%), than assumed before; 5. Global double porosity parameters estimates are: fracture spacing – 5 - 10 m, void fraction $N$ $10^{-2}$.

The best model above mentioned was run until year 2012 to match the available data for an extended time period (Figs. 8 and 9).

The match to production history is shown in Fig. 8, where model calibrated against transient enthalpies of individual production wells (1984-2006) was believed to reproduce total steam production of Mutnovsky PP’s after year 2006. We see a good convergence before 2006 (although this is just a check-balance test for the sum of individually calibrated rates), and rather good convergence in 2007-2008 years, nevertheless the model shows more optimistic total steam production rate compared to the observational data in year 2009 (Fig.8). At this time we have no clear answer why the model shows reservoir boiling increase after year 2008, while the observational data shows very stable steam mass fraction at level of 0.25-0.26 during that time. Transient enthalpy-flowrate analysis of individual production wells during the time period 2007-2012, as well as more information on reliability of individual and total production rates measurements - may help to answer this question.

Relatively good transient pressure match was obtained for wells 012 and 30, where capillary tubing systems were deployed (Fig. 9). Nevertheless, we are not able to explain in the model the sharp 20 bar pressure drop in well 30, and suspect this as an event of liquid inflow in a capillary tube at the time of V-Mutnovsky PP got into operation in a year 1999. We also put in a Fig. 9 pressure records of Rodnikovy well, located at Viluchinsky chloride hot springs 13 km apart from Mutnovsky production field (Fig.1, #18): this well was equipped recently with Ashcroft pressure gauge at wellhead and shows a total pressure decline 1.5 bar since Mutnovsky PP operation started.
TRANSIENT CHLORIDE MATCH (WELLS & HOTSPRINGS)

Standard TOUGH2- EOS1+tracer option was developed for the tracer uniformly distributed along two phases (steam and water). Hence, to use a chloride ion as a tracer - some code modification needed to keep chloride in a liquid phase and prohibit chloride appearance in steam phase. In order to do this the component-2 (mass fraction of tracer) was redistributed between steam phase (zero) and liquid phase \(\left(\frac{S_w^*\rho_w + S_s^*\rho_s}{S_w^*\rho_w}\right)\) using PAR-array in EOS subroutine.

Some correction of chloride concentration sampling from production wells was needed before calibration, since chemical analysis data are referenced to separated water. In order to do this, steam loss correction at sampling pressure (1 bar) used to convert those data to reservoir conditions.

It is also worth noting, that current iTOUGH2 does not use rate mass fraction in list of estimated parameters, hence we have to assume that the rate mass fraction of tracer (chloride-ion) in production well is equal to mass fraction of tracer (chloride-ion) in reservoir.

Chemical observational data includes transient mass chloride concentrations from 10 production wells and chloride hot spring sampling data (149 values during 1999-2006 years). Data of sampling Nizhne-Zhirovskoy chloride hot spring (Fig.1, #16) during 1986-2012 year time period were used too. This is the last adjacent to reservoir chloride hot spring survived after exploitation of Mutnovsky PP began. The following model parameters set was estimated as a result of natural state+exploitation iTOUGH2 inversion run (#12NSEX6T3): Main upflow chloride concentration – 144 ppm, NE upflow chloride concentration -120 ppm, cold water infiltration rate -72 kg/s (Inf, Fig. 4), fracture porosity – 0.8, fracture spacing – 12.1 m. Fig. 10 shows comparison of the model and production wells (029W, 013, 4E, 048, 037) transient chloride data for the best inversion scenario parameters set. In spite of cold water downflow dilution, chloride concentrations in most of the wells slowly rise due to boiling processes and subsequent chloride concentration increase in the reservoir. In opposite to wells Nizhne-Zhirovskoy hot spring (#16, Fig. 1) shows chloride concentration decline (Fig. 11). Additional source (45 kg/s) of cold water inflow was assigned in the north-eastern part of the model to reproduce this effect.

**Figure 9:** Model match with transient reservoir pressure: circles – observational data, red thick lines – modeling run #12NSEX6A2. Note: modeling pressures were adapted to pressure records elevations, well #012 data from (Maltseva et al., 2007 and JSC Geotherm).

**Figure 10:** Transient chloride concentration history match in production wells. Black circles – observational data (Maltseva et al., 2007), red thick lines – modeling run #12NSEX62AT3.

**Figure 11:** Transient chloride concentration history match in Nizhne-Zhirovskoy chloride hot spring. Black circles – observational data, red thick lines – modeling run #12NSEX62AT3.
TRANSIENT CO$_2$ MATCH

CO$_2$ is a dominant gas component (80%) in Mutnovsky production wells, hence TOUGH2 with EOS2 module is applicable for gas exploitation history description. We also assume in this modeling, that all non condensable gas (NCG) is CO$_2$. Although gas sampling from production wells was regularly performed during Mutnovsky exploitation, it is not easy to convert gas composition sampled at wellhead to mass fraction of gas in reservoir conditions (which were used as a primary variable in TOUGH2-EOS2), since phase relative permeabilities are not known well. Nevertheless, steam dominated wells data (26 and 016) seems to be appropriate for calibration purposes, since for this wells mass fraction of gas in reservoir is almost equal to rate mass fraction of gas at wellhead sampling point.

The following model parameters set was estimated using natural state+exploitation iTOUGH2-EOS2 inversion run (#12NSEX6CO2): mass fraction of CO$_2$ in high temperature upflows – 180 ppm, infiltration rate 93.6 kg/s, fracture porosity – 0.56, fracture spacing – 6.1 m. Fig. 12 shows satisfactory match of modeling and observational data for last phase of well 26 exploitation history, while underestimation of gas transient change in well 016.

Some model and data discrepancy may also be caused by TOUGH2-EOS2 disability for chemical fluid-rock interactions, which can generate or consume additional CO$_2$ due to carbonate minerals formation processes.

It is worth noting also some features of CO$_2$ distributions observed during natural state (long term run) modeling: CO$_2$ accumulation in low permeability cold elements of the model, where $P_{CO_2}$ reach values of 10 bars, that is larger than in high temperature upflow zone (0.19 bars) and in two-phase production reservoir (0.02 bars). This may be caused by higher CO$_2$ solubility in water under lower temperatures (<100°C) range. If natural state assumption is true, we can expect a cold low permeable CO$_2$-reach reservoirs as a markers of high temperature geothermal fields boundaries.

It also noted TOUGH2 convergence worsening caused by EOS1 to EOS2 model transfer, especially if double porosity MINC option is used.

Figure 12: Circles – observational data (grey – Kiryukhin et al, 2010, black – Maximov et al, 2011), red thick lines – modeling run #12NSEX62ACO2.

VERTICAL DEFORMATIONS MATCH

Vertical deformations ground leveling based on deep markers network, connected using high precision leveling measurements (1-st class of ground leveling), and wellhead markers secondary network (2-nd class of leveling). Surface leveling was conducted annually in September during 2004 – 2010 year time period. Ni 005A instrument was used for these purposes and measurements accuracy 1.0 mm/km was achieved. One deep marker located at a stable rock site in the western part of the Mutnovsky geothermal field was assigned as a reference marker. Three types of areas with different transient vertical deformations regime were identified based on these measurements.

1-st type area is located south from Mutnovsky PP (south-west part of Dachny site), in this place significant positive vertical deformations are observed: 2-4 mm/year in time period 2004 - 2005 years, 3-5 mm/year in time period 2005 - 2006 years, after that no significant vertical deformations observed (Fig.13, wells 029W, 26, 4E). This effect may be caused by boiling propagation into the deep high temperature parts of geothermal reservoir with subsequent pressure increase in shallow steam zone under the caprock of low permeable ignimbrites. Steam explosions happened in this area in 1989 year (during drilling well 029) and in 2003 year (nearly well 022) pointed to this mechanism too. At this time some of the wells (01, 08, 023) in this area have wellhead temperatures up to 240°C (corresponding pressure 33.5 bars) indicating potential hydrothermal explosion conditions in a depth.

2-nd type area of vertical deformations is located in North reinjection site (Fig. 13, well 027). At this site significant positive vertical deformations 6 – 14 mm/year took place during the time period 2006 – 2008 years. There was no significant vertical deformations observed during 2008 - 2009 years, then negative vertical deformations 5-8 mm/year occur during 2009 - 2010 years. These transient vertical deformations changes may indicate the rates of reinjection performed.
3-rd type area of vertical deformations is located on Verkhne-Mutnovsky site (Fig. 13, wells 049N, 055, 048). At this place subsidence took place since 2008 year with rate 6 – 18 mm/year. Total subsidence in Verkhne-Mutnovsky PP site accounted to 30-36 mm in a two years (accuracy of estimates is 2.5 mm). Similar behavior was recorded in east part of Dachny site (Fig. 13, wells 042, 013, 037).

DISCUSSION

Large-scale exploitation of Mutnovsky geothermal field started from 2000 year with fluid extraction up to 550 kg/s (660 MW) comparable with the average 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, 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)). Hydrothermal explosions and emerging of new boiling pots (#6) inside the exploitation area, disappearance (Voinovsky, #13 and Verkhne-Zhirovsk, #14) or degradation of chloride hot springs in the areas, adjacent to geothermal field (Nizhne-Zhirovskoy, #16) are recorded too (Fig. 1).

Analysis of the Mutnovsky field exploitation in relation to volcanic activity, as well as assessment of geothermal potential of active volcanoes structures need development of a numerical model of the extended geometry, including North Mutnovsky volcano-tectonic (NMVT) zone as a whole (Fig. 1). This big model volume is estimated as 468 km³ and the number of elements 7500+. On the other side, local problems of Mutnovsky geothermal reservoir production optimization (including meteoric downflows and reservoir boiling assessment) need models with more refined grid. 3D rectangular model of 500+ elements tested above may be used as a reference model in both cases. In this particular model TOUGH2 convergence worsens when double porosity MINC option is used, inability to assign MINC locally and having in account relatively small values of estimates for fracture spacing (5-10 m) - favor in a single porosity models use in future.

CONCLUSIONS

A 3D rectangular model of Mutnovsky geothermal field (Kiryukhin, 1996, Kiryukhin et al, 2012) calibrated based on 1984-2006 year history exploitation data (natural state temperatures, pressures, transient production wells enthalpies and reservoir pressures) was verified on additional available data of exploitation history until year 2012.
Model satisfactory matches transient total steam production observations during 2007-2008 years, while overestimate one in 2009 year. Modeling transient reservoir pressure satisfactory matches observations were obtained for the time period 2007-2009 year.

Model calibration (iTOUGH2-EOS1+tracer) against transient chloride in ten production wells during the time period 2002-2006 confirm basic model characteristics and additionally yield estimates of marginal chloride concentrations in high temperature upflow zones as 120-144 ppm, while additional downflow zone is needed in the model to match chloride hot spring transient data.

Model calibration (iTOUGH2-EOS2) against non condensable gas transient change in steam dominated production well 26 during the time period 2000-2010 is reasonably converged indicating NCG content in high temperature upflow as 180 ppm.

Transient vertical surface deformation changes qualitatively matches to thermal hydrodynamic model properties, such as: shallow steam reservoir conditions in south-west part of Dachny site; absence of significant reinjection effect in North Site, as estimated in a result of inverse modeling; estimated reservoir compressibility.

Transient enthalpy-flowrate analysis of individual production wells during time period 2007-2012, as well as more information on reliability of individual and total production rates measurements are needed to answer questions of model particular non convergence.

ACKNOWLEDGEMENTS

Authors appreciate to Y.F. Manukhin and The Agency of Natural Resources of Kamchatka for providing input data for Mutnovsky modeling. Authors also appreciate to S. Finsterle, who provided iTOUGH2-beta version to perform this study. Special thanks to students from Kamchatka State Technical University (group EPb-09), who help to build geological cross sections. This work was supported by RFBR under the project 12-05-00125 and FEB RAS under the projects 12-III-A-08-170, 12-I-P27-04.

REFERENCES


Инструкция по нивелированию I, II, III, IV классов. ГКИНП (ГНТА) -03-010-02. М.; ЦНИИГАиК, 2003. 135 с. (in Russian)


