DOI: 10.18454/PMI.2017.2.163

UDC 551.49+550.21

INVERSION MODELING OF THE NATURAL STATE AND PRODUCTION HISTORY OF MUTNOVSKY GEOTHERMAL FIELD IN 1986-2006

Aleksei V.KIRYUKHIN[1], Ol'ga O.USACHEVA[2]
[1] *Saint-Petersburg State University, Saint-Petersburg, Russia*
[2] *Institute of Volcanology and Seismology FEB RAS, Petropavlovsk-Kamchatsky, Russia*

Numerical 3D model of Mutnovsky geothermal field (Dachny springs), which consist of 517 elements and partially takes into account double porosity, was developed in 1992-1993 using computer program TOUGH2. Calibration of the model was based on data from test yield of the wells and initial distribution of temperature and pressure in the reservoir. This model was used for techno-economic justification of power plant construction (Mutnovskaya GeoES, 2002). The model was recreated in the program PetraSim v.5.2, the calibration was carried out using additional data on production history before year 2006 and inversion iTOUGH2-EOS1 modeling. Comparison of reservoir parameters, estimated using inversion modeling, with previous parameter estimations (given in brackets) showed the following: upflow rate of heat-transfer agent in natural conditions 80.5 (54.1) kg/s, heat flux enthalpy 1430 (1390) kJ/kg, reservoir permeability $27 \cdot 10^{-15}$-$616 \cdot 10^{-15}$ ($3 \cdot 10^{-15}$-$90 \cdot 10^{-15}$) m^2. Inversion modeling was also used to estimate reinjection rates, inflow of meteoric water in the central part of geothermal field and compressibility of reservoir rocks.

Key words: 3D-modeling, iTOUGH2, Mutnovsky, geothermal, Kamchatka

***How to cite this article*:** Kiryukhin A.V., Usacheva O.O. Inversion Modeling of the Natural State and Production History of Mutnovsky Geothermal Field in 1986-2006. Zapiski Gornogo Instituta. 2017. Vol. 224, p. 163-169. DOI: 10.18454/PMI.2017.2.163

Introduction. The region under consideration has been thoroughly studied and described by many researchers [1, 3, 5, 6, 12]. Various conceptual models of Mutnovsky field have also been proposed [1, 10]. Exploitation of Mutnovsky geothermal field (Fig.1) with installed power station capacity of 62 MW is crucial for the development of renewable thermal energy in Kamchatka. Furthermore, acquired experience can be used in the exploitation of other large geothermal fields in Kurilo-Kamchtsky region, as well as in understanding the connection between volcanic, hydrothermal and seismic activity.

From the beginning of full-scale exploitation, in the course of the first several years (2002-2006) the content of water steam in the reservoir significantly dropped: from 0.46 to 0.27 (Fig.2). Certain production wells were put out of operation (049N, 055, 5E, 4E, 053N, 017N) due to decline of wellhead pressure. There are some signs that local meteoric waters flow into the reservoir.

Field exploitation, ongoing since 2000 with the heat-transfer agent being extracted at the rates up to 500 kg/s (600 MW), is comparable to energy capacity of neighboring active volcanoes: Mutnovsky (8 km, 190 MW) and Gorely (10.5 km, 100 MW). Field exploitation is followed by hydrothermal eruption activity of Mutnovsky volcano after 40 years of being quiet (hydrothermal eruptions in the crater on 17th March 2000, in April 2007 and May 2012) [2]; beginning of fumarole activity of Gorely volcano in 2010; vanishing of crater lakes on Mutnovsky (2004) and Gorely (2012). The process of exploitation is also accompanied by enhanced seismic activity. Since February 2009 till May 2012, Kamchatsky branch of Geophysical Service, Russian Academy of Sciences, registered 11 earthquakes of magnitude 1.3-2.0 at the depth of 2-6 km.

Observations of the producing area have revealed hydrothermal eruptions and initiation of new boiling pools, decline of chloride hot springs (reduced flow rate, lowered mineralization), a 2-bar pressure drop in the monitoring well located near Vilyuchinsky springs, vanishing of Voinovsky and Verkhne-Zhirovsky springs, substantial chlorum reduction in Nizhne-Zhirovsky spring.

All the above mentioned implies that the process of field exploitation and phenomena related to it require thorough hydrogeological analysis, including modeling in order to improve existing

DOI: 10.18454/PMI.2017.2.163

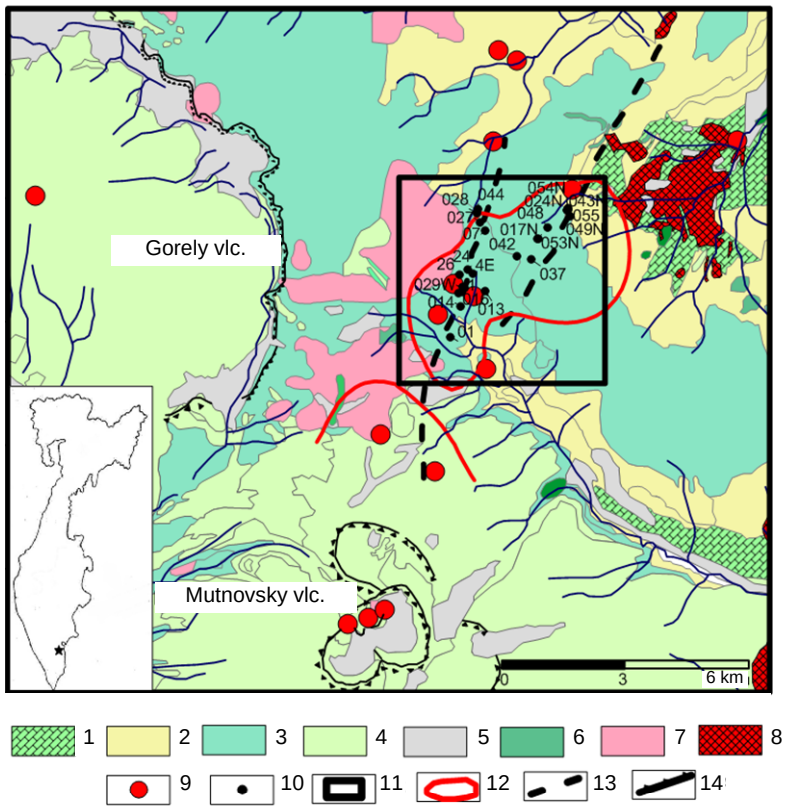


Fig.1. Sketch geological map of Mutnovsky geothermal field

1 – Tertiary igneous-sedimentary rocks; 2 – tuffs and lavas – basaltic, andesibasaltic, andesite-dacitic – belonging to Asachinskaya suite and Alneyskaya series; 3 – Quaternary basalts and their tuffs; 4 – extrusive rocks of Mutnovsky and Gorely volcanoes; 5 – recent fluvio-glacial sediments and glaciers of Mutnovsky volcano; 6 – Quaternary dykes and basaltic stocks; 7 – extrusions of rhyolites and dacites; 8 – Tertiary diorite intrusions; 9 – fumarole fields and thermal springs; 10 – production and injection wells; 11 – boundaries of the model; 12 – isolines of temperatute 230 °C at the absolute elevation –250 m; 13 – projections of production fractures at the absolute elevation –250 m; 14 – calderas

methodology of thermal water prospecting and, in particular, methods to estimate their resources and commercial reserves.

Model assembly of Mutnovsky geothermal field. The first thermo-hydrodynamic model of Mutnovsky geothermal field was assembled in 1991 in Lawrence Berkeley National Laboratory, USA, using computational program TOUGH2 [13] and supercomputer CRAY-X-MP. The calibration of the model was carried out using production history of 1984-1987 and initial distribution of temperature and pressure (according to data by P.P.Blukke, N.P.Asaulova et al. Report … with estimation of heat-transfer agent reserves to justify first phase construction of Mutnovskaya power station with capacity 50 MW, 1987). Application of this model to forecasting different options of field exploitation are published in works [4, 11].

With the development of efficient pre- and post-processors for TOUGH2-modeling, as well as the opportunity of inversion iTOUGH2 modeling [7-9], the speed of model assembly, its testing and application has substantially increased. This allowed to recreate the model in 1996 with the help of pre-processor PetraSim v.5.2. This model can be used to estimate reserves of Mutnovsky field, as it contains minimum number of necessary elements to describe existing reservoir. It belongs to the «hydraulic type» of models, in Russia they are applied to estimate commercial reserves of deposits in the third category of difficulty.

As an addition to the previous model, 20 wells have been specified – 16 production and 4 injection ones (Fig.3). Production wells 016 and 26 are steam-dominated, they have been set in the second layer of the model, represented by rhyolitic tuffs (domain Tuff2 in the model). Production wells 01, 014, 029W, 24, 055, 048 and injection wells 027 (+028+044), 07 have been set in the middle layer, containing igneous and sedimentary rocks (area Sand1 in the model). Production wells 1, 4E, 013, 042, 037, 053N, 017N, 049N and injection wells 043N, 054N have been set in the fourth layer from the top (intrusive contact zone, area Cont1 in the model). Production wells are set in the model with a variable flow rate; for injection wells enthalpy of injected water is additionally specified according to data by K.I.Maltseva et al. (report on re-calculation of commercial reserves of heat-transfer agent for Mutnovsky steam-hydrothermal field as on 31.12.2006)

DOI: 10.18454/PMI.2017.2.163

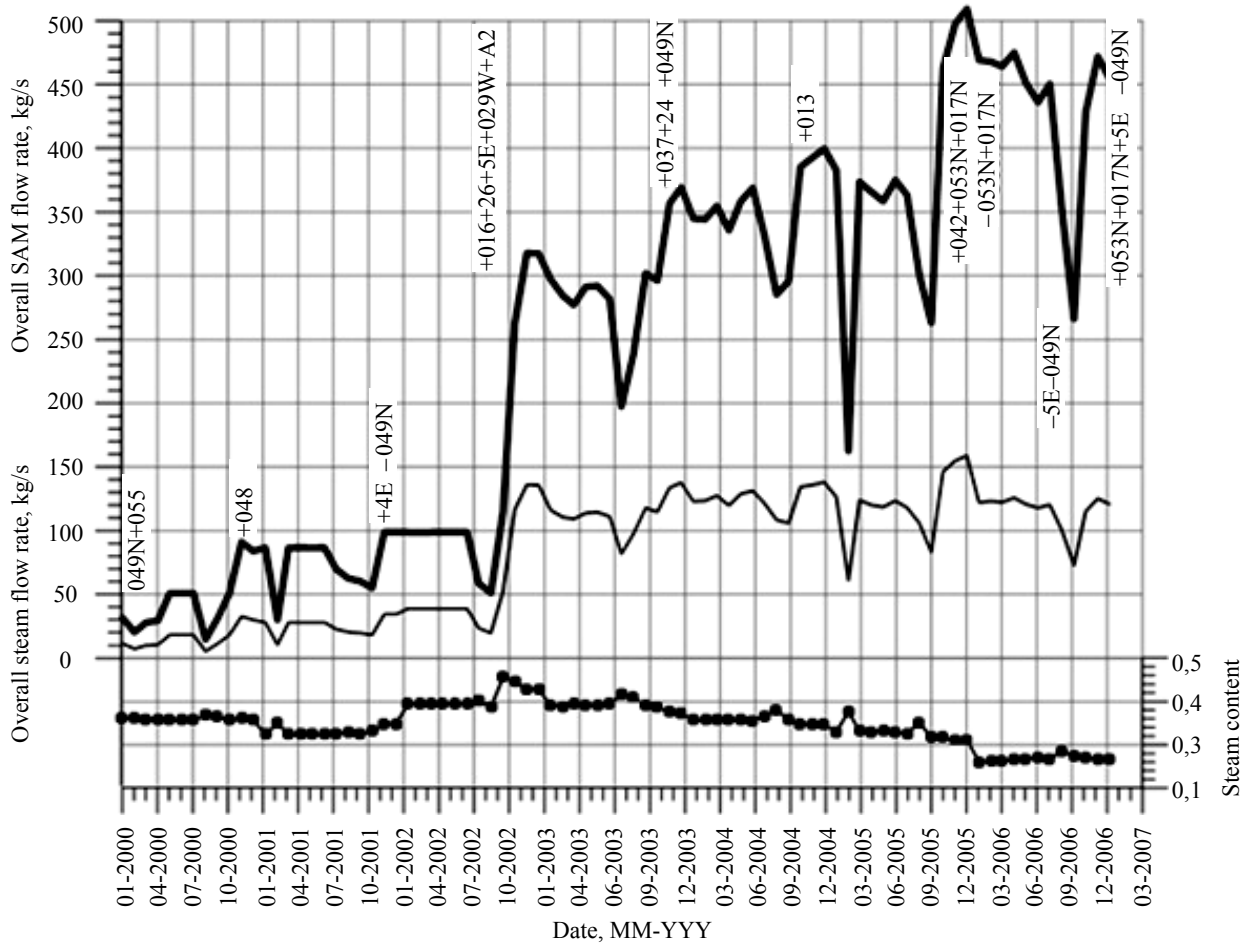


Fig.2. Overall production of steam-and-air mixture (SAM) on Mutnovsky geothermal field – upper curve; steam production – middle curve and steam content (lower curve). Time axis is presented in month-year format (MM-YYY)

Certain elements of the model, containing operating wells, were identified to have double porosity. Inclusion of double porosity in the model appeared to be an essential step to reproduce enhanced enthalpy values of some operating wells. Wells 016, 26, 01, 1, 24 and others demonstrate enthalpy exceeding the one of initial liquid water, which is indicative of local underground boiling in the reservoir. Specification of double porosity in the model has been done through volume reduction of initial permeable element and attachment of low-permeability «matrix» element with a total volume equal to the initial one.

Inversion iTOUGH2-EOS1 modeling of the natural state and production history. Inversion modeling has been organized in the following manner: at the first stage the model was run to the moment of its current state; the second stage included modeling of production history for the period 1987-2006 using initial data obtained at the first stage.

Input modeling data. Initial state calibration of the model was performed with the help of eight measured values of well temperature, confirmed by geochemical data (Na-K-geothermometers). To test production history calibration, pressure values were taken from monitoring wells 30 and 012 for the time period 1995-2006 (total number of measurements – 51) and adjusted to depths – 250 and –750 m respectively. Data on monthly average values of enthalpy for 14 production wells: 016, 26, 01, 1, 24, 048, 042, 029W, 037, 013, 055, 049N, 4E, 017N – were also used for calibration – 592 values for time periods 1984-1987 and 2000-2006. Additional monitoring of flow rate and enthalpy were implemented for several wells (016, 26, 01, 1, 24, 042, 029W, 037, 013, 4E, 017N) on Mutnovskaya geothermal station, based on flow rate differences before and after individual wells have been shut-off.

DOI: 10.18454/PMI.2017.2.163

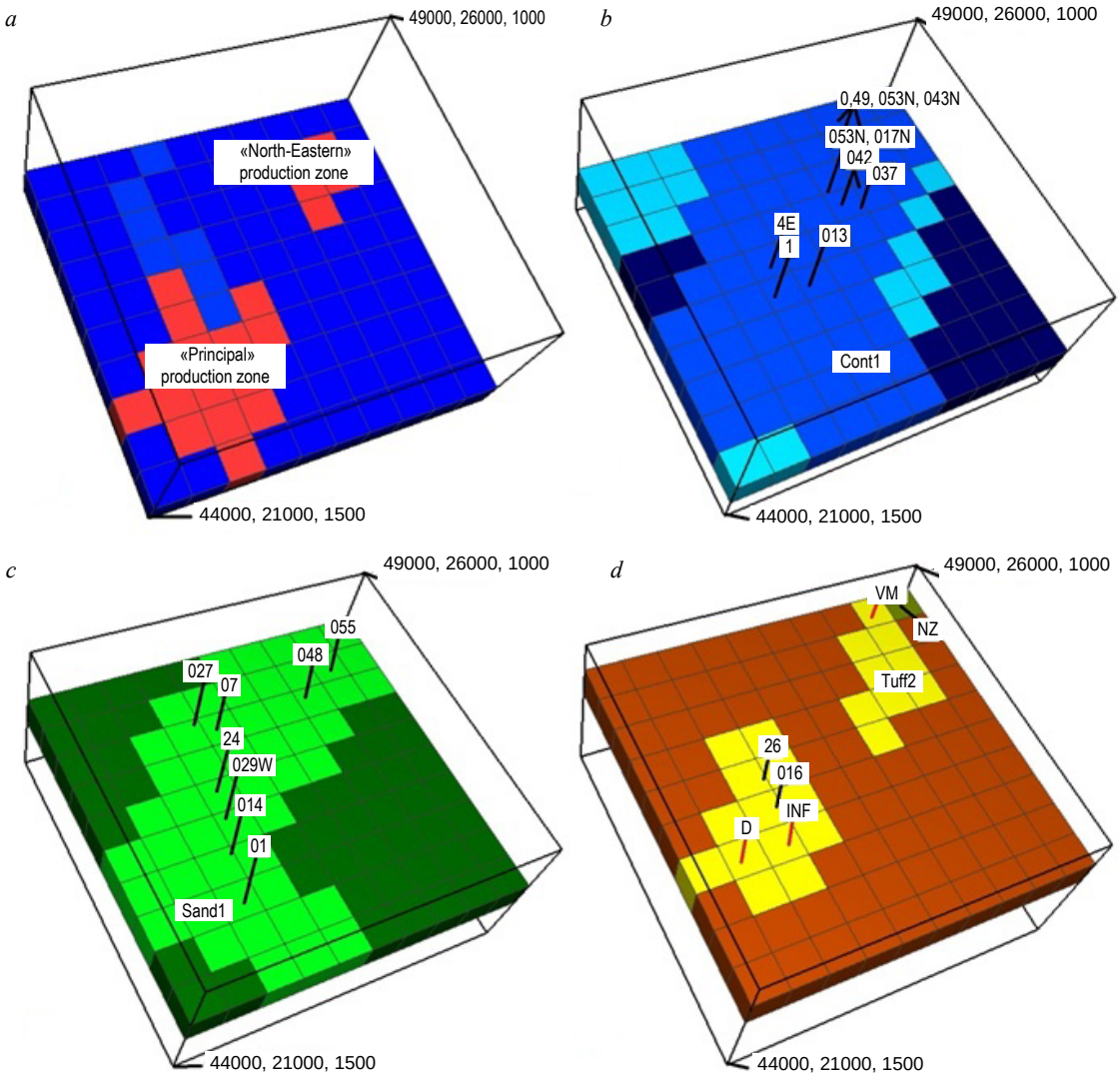


Fig.3. 3D numerical model of Mutnovsky geothermal field: *a* – lower layer (–1250 m abs.), including inflow zones of heat-transfer agent: «Principal» and «North-Eastern»; *b* – second layer from the bottom (–750 m abs.), containing permeable domain Cont1, associated with intrusive contact zone; *c* – third layer from the bottom (–250 m abs.), including permeable domain Sand1, associated with igneous and sedimentary rocks; *d* – fourth layer from the bottom (+250 m abs.), containing domain Tuff2, associated with rhyolitic tuffs. Thermal occurrences in the model: D – Dachny steam jets, VM – Verkhne-Mutnovsky steam jets, NZ – group of hot springs (+250 m abs.) Production wells are displayed as numbers

Estimated parameters. The multitude of estimated parameters included: flow rates of rising currents (two upflow zones, within which mass sources have been set, «Principal» and «North-Eastern»); reinjection rates – rates of four groups of injection wells (027 (+028+044), 07, 043N, 054N (+024N)). Fracture permeability has been estimated for the following layers (from top to bottom): rhyolitic tuffs (area Tuff2), sandstones (area Sand1), intrusive contact zone (area Cont1) and diorite intrusion (MagmF); natural discharge (three main discharge areas: Dachny – D (steam), Verkhne-Mutnovsky – VM (steam) and hot water discharge represented by several groups of hot springs, in the model introduced as NZ); infiltration rate (reservoir recharge by the downflow of meteoric water takes place near Utiny lake as well as through poor-quality casing of the old wells drilled in 1980s, it is estimated in one of the elements on the surface of the model with enthalpy value of 42 kJ/kg); double porosity parameters (the model uses orthogonal 3D system of fractures with the share of fracture space FF and distance between fractures FS); compressibility of rocks.

DOI: 10.18454/PMI.2017.2.163

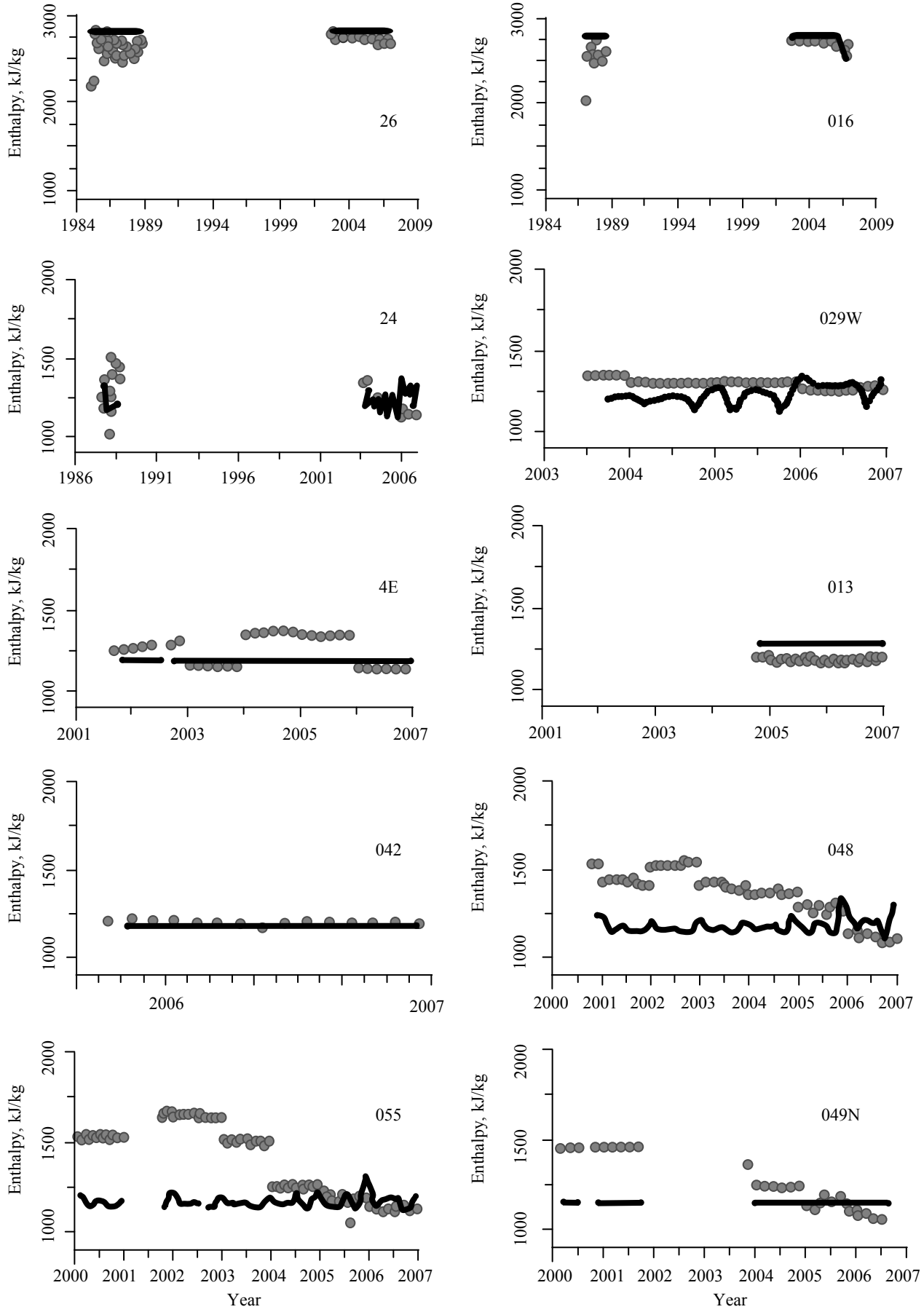


Fig.4. Comparison of modeled and actual values of enthalpy: grey circles – observed values, black line – modeling results (scenario 12-NS-EX-6)

DOI: 10.18454/PMI.2017.2.163

Estimation results. Modeling of five different scenarios iTOUGH2-EOS1 (12-NS+EX-11, 7, 8, 11A, 12) leads to the following results. In scenario 11A reinjection rate is estimated at 42-85 % of its actual value (62 % of the overall flow rate). Objective functions get significantly reduced, if reinjection rates are set to zero (scenarios 7, 8, 11A, 12). The minimal obtained objective function corresponds to scenario 12. However, this scenario is also characterized by significantly high standard deviation of temperature (6.2 °C), pressure (1.9 bar) and enthalpy (179 kJ/kg) from their observed values. Deviations of the model exceed corresponding measurement errors. Besides, systematic under-estimation of enthalpy (71 kJ/kg) and temperature (14.9 °C) as well as systematic over-estimation of pressure (–0.9 bar) were detected.

The situation was partially improved with the help of discharge regulation in the D element of the model: objective function decreased and temperature deviations were reduced to the point of 7.4 °C. As a result, the following estimations were obtained in the improved scenario (12NS-EX-12A): flow rate of the «Principal» rising current – 60.2 kg/s, flow rate of the «North-Eastern» rising current – 20.3 kg/s, tuff permeability – $27 \cdot 10^{-15}$ m^2, sandstone permeability – $85 \cdot 10^{-15}$ m^2, contact zone permeability – $616 \cdot 10^{-15}$ m^2, intervals between fractures – 4.3 m, fracture porosity – 0.42, infiltration rate – 103 kg/s, compressibility of sandstones and contact zone rocks – 1.3E-7 Pa^{-1}.

Additional calibration of the model using measurements of initial temperatures. Measurement data on well temperatures for Mutnovsky geothermal field were acquired at the prospecting stage in the process of well drilling: there were 72 temperature records from well bottoms; 29 out of 72 measurements, obtained from positions located closer than 250 m from element centers, were chosen as additional calibration points for the natural state model.

Straight iTOUGH2 parameter runs (12NS-EX-12B) demonstrate systematic under-estimation of temperature (7.5 °C), caused by understated values of upflow enthalpy, obtained with Na-K-geothermometers (308 °C).

Additional inversion modeling using upflow enthalpy as an estimated parameter with upper bound of 1450 kJ/kg (318 °C) (12-NS-EX-6, running with six adjusted parameters, all the rest taken from scenario 12) led to the following results: enthalpy of the «Principal» rising current – 1432 kJ/kg (water 314 °C), enthalpy of the «North-Eastern» rising current – 1406 kJ/kg (water 311 °C), intervals between fractures – 4.5 m, fracture porosity – 0.36, downflow – 78 kg/s, compressibility of sandstones and contact zone rocks – 1.4E-7 Pa^{-1}. Although this scenario over-estimates temperature (–7.9 °C), it can be regarded as satisfactory, considering only partial recovery of well bottom temperatures used for calibration.

Under mentioned parameters, modeled enthalpy values conform with the actual enthalpies of production wells in the central part of Mutnovsky field: wells 26, 016, 24, 029W, 4E, 013, 042 (Fig.4). Comparison of modeled and actual pressure values, calculated using water levels in 11 wells – scenario 12-NS-EX-6, also shows their adequacy (0.3 bar), which is acceptable considering uncertainty of pressure calculations based on well water levels for high-temperature fields.

Conclusion. Numerical TOUGH2-EOS1 model of Mutnovsky geothermal field [11] has been recalibrated using data on the natural state of the deposit and its production history in 1984-2006. The process of recalibration using inversion modeling iTOUGH2-EOS1 demonstrates good accordance with the actual enthalpy of production wells, which reflects reservoir bulk properties, and allows to specify reservoir characteristics.

Reservoir permeability is a sequence higher than the one in 1996 model, especially in its lower part, associated with intrusive contact zone (600-800$\cdot 10^{-15}$ m^2 at the depth –750-1250 m);

DOI: 10.18454/PMI.2017.2.163

meteoric water inflow into the central part of the field in the process of its exploitation – more than 80 kg/s; reinjection rates are estimated significantly lower than overall extraction rate of the heat-transfer agent; rising currents have higher temperature (314 °C) and greater flow rate (+50 %) than it was believed earlier; parameters of double porosity demonstrate relatively homogenous nature of the geothermal reservoir (distance between fractures 5 m, fracture space $N \cdot 10^{-3}$).

Acknowledgements. *Authors express their gratitude to Yu.N.Manukhin and the Agency of Mineral Resources of Kamchatka for actual data for Mutnovsky field modeling. Authors also express their gratitude to S.Finsterle for consultations on the application of iTOUGH2 software. The research has been carried out with financial support from Russian Science Foundation, project 16-17-10008, and Russian Foundation for Basic Research, project 15-05-00676.*

REFERENCES

1. Vakin E.A., Kirsanov I.T., Kirsanova T.P. Thermal Field and Hot Springs of the Mutnovsky Volcanic Area. Hydrothermal Systems and Thermal Fields of Kamchatka. Vladivostok: Izd-vo DVNTs, 1976, p. 85-114 (in Russian).

2. Gavrilenko G.M., Mel'nikov D.V. Fifteen Years in the Life of the Volcano Mutnovsky. *Priroda*. 2008. N 2, p. 54-58 (in Russian).

3. Geothermal and Geochemical Researches of High-Temperature Hydrothermal. Ed. by V.M.Sugrobov. Moscow: Nauka, 1986, p. 209 (in Russian).

4. Kiryukhin A.V. Modeling Studies of the Geothermal Fields. Vladivostok: Dal'nauka, 2002, p. 216 (in Russian).

5. Leonov V.L. Structural Conditions of Localization of High-Temperature Hydrothermal. Moscow: Nauka, 1989, p. 104 (in Russian).

6. Celyangin O.B. New About Mutnovski Volcano. *Vulkanologiya i seismologiya*. 1993. N 1, p. 17-35 (in Russian).

7. Finsterle S. iTOUGH2 User's Guide: Report LBNL-40040. Lawrence Berkeley National Laboratory. Berkeley, California, 1999, p. 130.

8. Finsterle S. iTOUGH2 Command Reference: Report LBNL-40041. Lawrence Berkeley National Laboratory. Berkeley, California, 1999, p. 233.

9. Finsterle S. iTOUGH2 Sample Problems: Report LBNL-40042. Lawrence Berkeley National Laboratory. Berkeley, California, 1999, p. 88.

10. Kiryukhin A.V. High temperature fluid flows in the Mutnovsky hydrothermal system, Kamchatka. *Geothermics*. 1993. Vol. 23. N 1, p. 49-64.

11. Kiryukhin A.V. Modeling Studies: the Dachny Geothermal Reservoir, Kamchatka, Russia. *Geothermics*. 1996. Vol. 25. N 1, p. 63-90.

12. Povarov O.A., Nikolsky A.I. Experience of Creation and Operation of Geothermal Power Plants in Cold Climate Conditions. Proc. World Geothermal Congress 2005. Antalya, Turkey, 24-29 April 2005, p. 1-9.

13. Pruess K., Oldenburg C., Moridis G. TOUGH2 User's Guide, version 2.0, Report LBNL-43134. Lawrence Berkeley National Laboratory, Berkeley, California. 1999, p. 197.

***Authors*: Aleksei V. Kiryukhin,** *Doctor of Geological and Mineral Sciences*, *Professor*, *AVKiryukhin2@mail.ru* (*Saint-Petersburg State University*, *Saint-Petersburg*, *Russia*), **Ol'ga O.Usacheva,** *Junior Researcher*, *LeL89@yandex.ru* (*Institute of Volcanology and Seismology FEB RAS*, *Petropavlovsk-Kamchatsky*, *Russia*).

The paper was accepted for publication on 19 January, 2017.