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MODELING STUDY OF THE PAUZHETSKY GEOTHERMAL FIELD, KAMCHATKA, RUSSIA

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ABSTRACT

Pauzhetsky geothermal field is a liquid dominated geothermal field located in the south of Kamchatka (Fig. 1). Exploitation of the 5 MWe power plant started since 1966. Hydrogeological model of the Pauzhetsky field based on the integrated analysis of the lithological units data, temperature, pressure and production zones and natural discharge distributions. One-layer "well by well" model with specified vertical heat and mass exchange conditions used to represent main features of the production reservoir. Numerical model development was based on TOUGH2 code (Pruess et al., 1999) and HOLA wellbore simulator (Aunzo et al., 1991). Modeling study of the natural state conditions was targeted on temperature distribution match to estimate the natural high temperature upflow parameters: reliable part of the mass flowrate estimated as 204 kg/s with the enthalpy of 830 – 875 kJ/kg. Modeling study of the 1964 – 2000 year exploitation period of the Pauzhetsky geothermal field was targeted to match the transient reservoir pressure and flowing enthalpies of the production wells. Modeling study of the exploitation confirmed the "double porosity" in the reservoir with active volume of "fractures" 10-20% and thermo-mechanical response to reinjection (including change of the porosity) as a key parameters of the model. The calibrated model of the Pauzhetsky geothermal field used to forecast different exploitation scenarios: 8.5 – 17.5% steam production rate decline (at 2.7 bars) during the next 20 years of the exploitation estimated in the model.

INTRODUCTION

Long-term geothermal fields exploitation data is a valuable information source for numerical models applications to understand more clear heat and mass processes in geothermal reservoirs and geothermal field reserve estimation. The last is important for future technical and economical decisions regarding power plant construction projects.

The earlier decision to build a 5 MWe Pauzhetka power plant was made one year after the flow test conducted in 1962-1963 years, which demonstrate stable flowrate of 120–125 kg/s with enthalpy 630–800 kJ/kg at 2.8 bars wellhead pressure (Pauzhetka et al., 1965). Nevertheless, as much mass flowrate extracted, the larger reservoir response in enthalpy, temperature and pressure decline was observed. Reinjection was started in 1979 to compensate mass negative balance and maintain reservoir pressure. "Surprisingly", North site of the field was taken out in 1999 due to significant enthalpy drop of the exploitation wells. The Central site of the Pauzhetsky field was influenced by temperature decline too. In contrary, the steam production demands from Pauzhetsky power plant increased.

This case put the numerical modeling in position of the instrument of "judgement", while reliable reservoir data (temperature logs in key monitoring wells and production wells enthalpy-flowrate data) are definitely needed to back this judgement well.

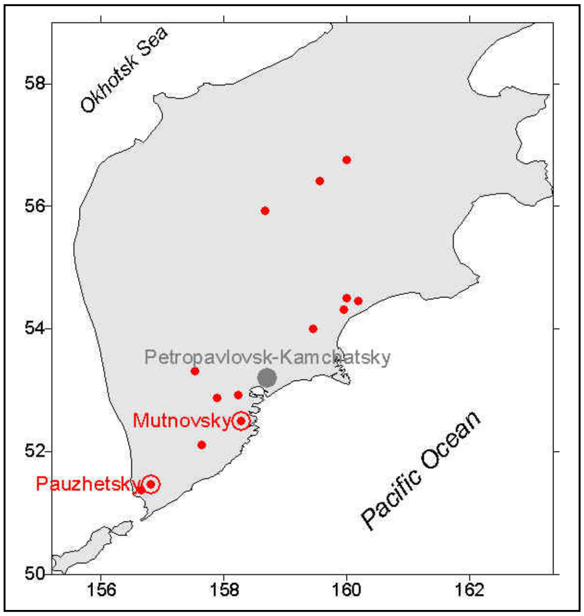

Figure 1. Location of the Pauzhetka geothermal field, Kamchatka, Russia.

HYDROGEOLOGICAL MODEL

Pauzhetsky geothermal field occur in the monocline slope of the Kambalny ridge inside of the Pauzhetka volcano-tectonic depression (Fig. 2). The oldest rocks penetrated by wells at 650 m depth are miocene sandstones. Pauzhetka tuffs (N_2-Q_1) include welded tuffs, tufficious conglomerates, and psefiitic tuffs. The caprock represented by 100 m thick dacitic alevropelitic tuffs. Rhyolite and andesite-dacite extrusions (domes and ridges) from 0.01 to 8 km^2 size scale are common.

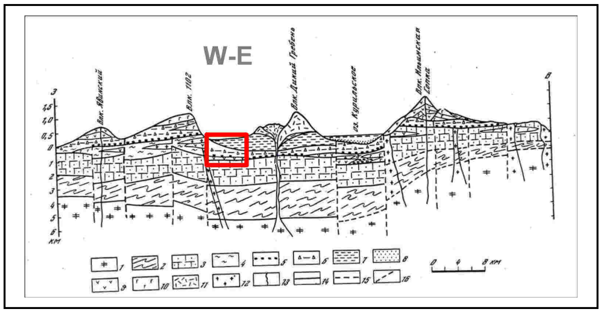

Figure 2. Geological cross section of the Pauzhetka volcano-tectonic depression (Dolgozhivushy… 1980), rectangle represent modeling area.

1-basement rocks, 2-Cretateous rocks, 3-Miocene sandstones,4-6-Neogene-Lower Plestocene lavas, tuffs, conglomerates, 7- Lake deposits (Q_{1-3}), 8-Kurile Lake, 9-andesites, 10-basalts,11- dacites, 12-diorite intrusions, 13- Volcanoes channels 14-1-boundaaries, 16- faults.

Natural thermal discharge include hot springs with measured rate 31 kg/s, and steam grounds (Verkhnee and East with the total discharge of 0.7 MWt). Reservoir temperature 180–220 °C (Fig. 3), thermal fluid is characterized by Cl-Na, CO_2-N_2 chemical composition with mineralisation of 2.7–3.4 g/kg. Hydroisotope (δD, δO_{18}) composition of the thermal fluids correspond to Kurile Lake water – Kambalny Ridge cold springs range, which demonstrate meteoric origin of the thermal fluids.

Cumulative rate per well vs depth graph (Fig. 4) shows the most production occur in the interval from 100 to 800 m depth, terminating at 23.2 kg/s flowrate value. This interval include lower and middle part of the Pauzhetka tuff formation (N_2-Q_1 pau$_{1,2}$) and Golyginsky Layer (N_2 gol). This is a clear indication layer type of the permeability in the Pauzhetsky geothermal field, and the bottom of the Pauzhetka tuffs formation may be used as a marker of the "center" of such production layer. Well logging analysis show the average thickness of production zone is 334 m (including 4.3 subproduction zones, in average).

Dacite extrusion complex (Q_{2-3}), which located inside of the 190°C zone, seems in a charge of the structural control of the temperature and permeability distribution (Fig. 5). This complex penetrated by wells 111, 124, 105, 101, 123, 107, 106, 131 at depth more than 50 m.

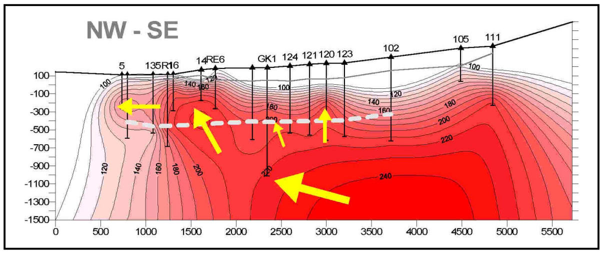

Figure 3. Cross section of the Pauzhetka geothermal field: temperature distributions and flows.

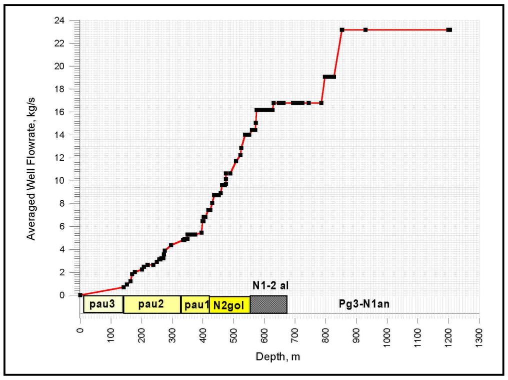

Figure 4. Averaged well production rate vs depth.

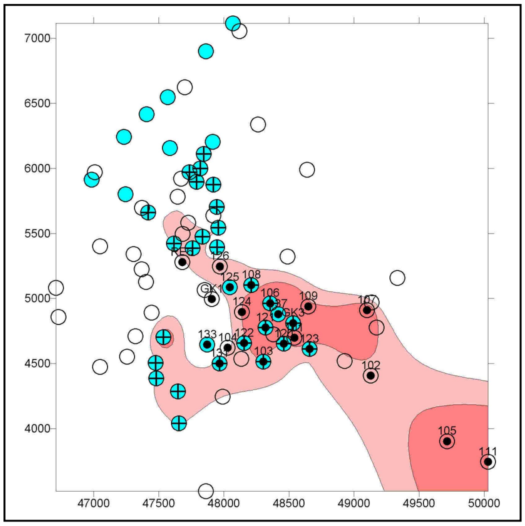

Figure 5. Structural control of the Pauzhetsky production reservoir. Wells, penetrated dacite extrusion Q_{2-3} marked by black circles, production wells marked by filled circles with crosses, reinjection wells with high productivity marked by filled circles. Max observed temperature counters 195°• and 200°• (filled) are shown too.

NUMERICAL MODEL

Geothermal reservoir was assigned in the model as a layer system with an average thickness 700 m and caprock 100 m thick. The centers of the elements were assigned at elevations of the bottom of the Pauzhetka tuffs formation. For this purposes A-mesh grid generator used. The total number of the elements is 131, including 66 well elements, 32 “FFF-elements” to fill empty regions, 32 boundary B-elements and C 1 special element to assign heat exchange in the caprock (Fig. 6).

Mass sources in the model were assigned where the natural high temperature upflows assumed, with the enthalpies corresponding to the liquid water temperature. Heat sources were assigned at the bottom of the model layer to reproduce background conductive heat flow (6.3 10^{-3} W/m2). Heat exchange in the caprock was approximated as a stationary conductive heat flow losses through C 1 inactive element (with specified 5^{o}C temperature) from model elements. Lateral boundary pressure and temperature conditions were assigned to be constant in the B-elements of the model. Discharge conditions were assigned through additional inactive elements P1 1, 135 1, 5 1 and 142 1 with the centers at earth surface elevations, constant atmospheric pressure and 100^{o}C discharge temperature. These elements were vertically connected to P1, 135, 5 and 142 elements of the model, where the most of the natural discharge in form of the hot water springs located.

Rock properties are very much influenced by hydrothermal alteration processes. The most permeable and completely altered (zeolites, chlorites) production zone is characterized by 0.20 porosity and 1500 – 1800 kg/m^3 density, while less permeable outside domains are 50% altered (illites, chlorites, calcite, quartz) and charactrized by 0.08-0.20 porosity and 2100 – 2500 kg/m^3 density.

NATURAL STATE MODELING

Modeling study of the natural state conditions was targeted to temperature and pressure distribution match to estimate the natural upflow parameters (mass rate, enthalpy) and total permeability distribution. Fig. 7 show modeling and measured temperature match with mass sources referenced in Table 1, and Fig. 8 represent corresponding permeability domains distribution. Its worth to note measured temperature distribution was obtained after exploitation began, that was a reason that in some regions of the field the greater modeling temperatures assumed to be “valid”. Permeability estimated in domains rock1, rock2 and rock3, correspondingly (Fig. 8). Natural upflows estimated in the model are 204 kg/s with the enthalpy of 830-875 kJ/kg (in total for the North site and Central site of the Pauzhetsky geothermal field) and 120 kg/s with the enthalpy of 900 kJ/kg (South-East site). Fig. 9 show flows distributions in the model. Streamline directed outside of the Central site of the field in all directions, including south-east direction. Note, that is in a contrary with the previously suggested conceptual model (Pauzhetka …,1965), assumed the natural high temperature flow recharge came from the Kambalny ridge side.

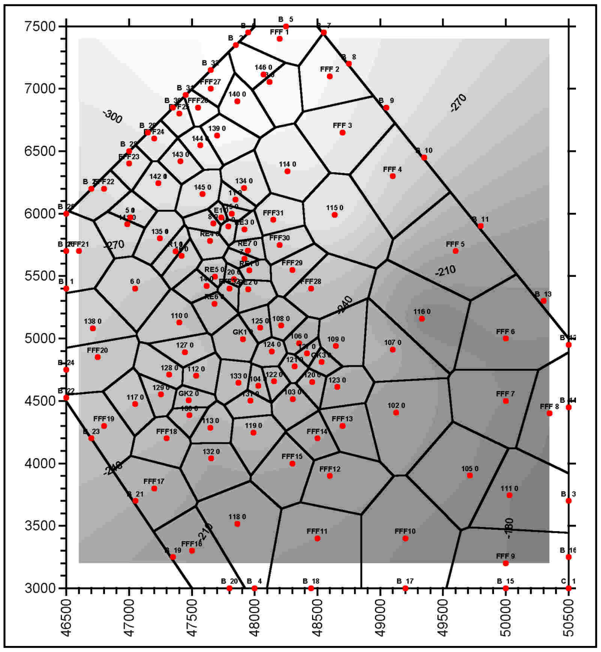

Figure 6. Numerical grid geometry, filled counters are modeling layer elevations (m.a.s.l.).

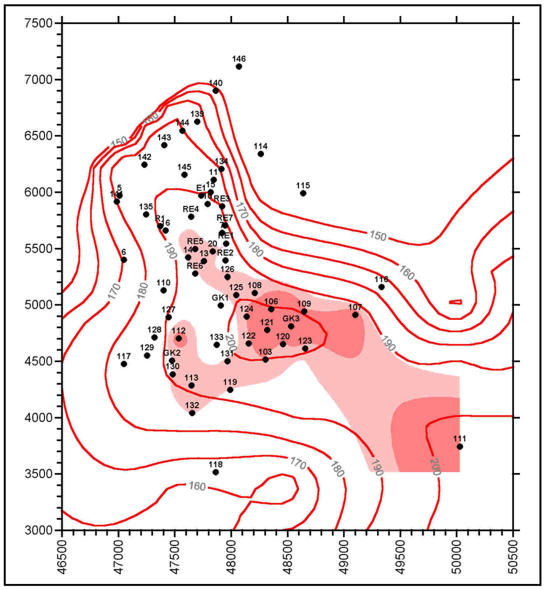

Figure 7. Natural state: modeling temperature distribution (counters) and observed max temperature distribution (filled counters).

Table 1. Model sources, which yield natural state temperature match (model and field data).

Element	Mass rate, kg/s	Enthalpy, kJ/kg	Element	Mass rate, kg/s	Enthalpy kJ/kg
103	6	875	130	6	830
123	6	875	113	6	830
131	6	875	119	6	830
133	6	875	FFF14	6	830
122	12	875	FFF13	6	830
FFF32	6	830	14	6	830
121	6	875	20	6	830
120	6	875	RE1	6	830
109	6	875	RE4	6	830
137	6	875	16	6	830
106	6	875	FFF18	6	830
124	6	875	132	6	830
GK1	6	875	102	24	875
125	6	875	107	12	875
RE6	6	830	105	32	898
108	6	875	111	32	898
112	6	830	FFF 9	32	898
GK2	6	830	GK3	6	921

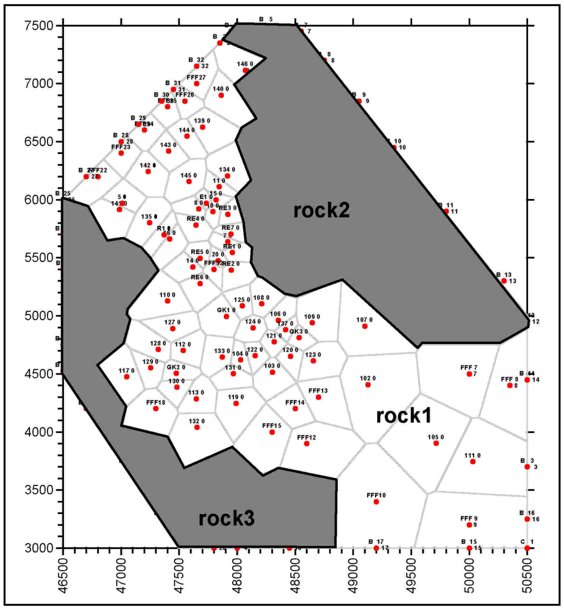

Figure 8. Model domain permeability distribution: rock1, rock2 and rock3 permeabilities estimated as 100 mD, 10 mD and 3mD correspondingly.

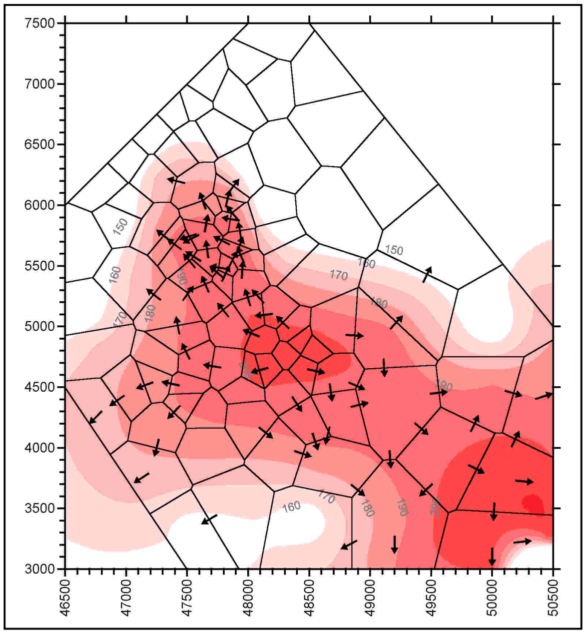

Figure 9. Natural state model: temperature distribution and mass flows (>5 kg/s).

EXPLOITATION 1964-2000 MODELING

Modeling study of the exploitation was a calibration of the model based on monthly flow-enthalpy production data pressure transient data matches (Fig. 10, 11). Flow-enthalpy data based on direct measurements of the production wells (all wells are equipped with individual separator units) and Na-K geothermometer estimations of the enthalpy, calculated from the chemical composition of the separate liquid phase. There was no direct measurements of the bottomhole pressure records in monitoring wells. So, to estimate pressure in monitoring wells the following formulae used:

$$P = P_{atm} + \int_{z0}^{z1} \rho(T,z)\ g\ dz$$

- where P - pressure estimated at z1 elevation, P_{atm} - atmospheric pressure, z0 - water level elevation, ρ(T,z) - water density in well, depending of temperature and depth z, g - gravitational constant.

Ten monitoring wells in the Pauzhetsky field were found to be useful for such pressure estimations based on synchronous temperature logs and water level measurements (114, 115, 117, 119, 132, 5, 6, P-1, 8, 124), although these data are found to be not regular and cover not all time period of the exploitation (1964-2000 years).

Fig. 12 show examples of the transient pressure matches in the monitoring wells 5 and 6, and Figs. 13–14 examples of the transient enthalpy matches in the production wells RE-1, 106 and 108.

The following corrections of the natural state model were found to be nesessary to match the transient geothermal field exploitation data (enthalpy and pressure transient data):

(1) Pressure values in boundary B-elements

(2) Permeability coefficients 100 мD in rock1 domain, 10 mD in rock2 domain, 3 mD in rock3 domain (Fig. 8).

(3) Rock compressibility 5.0 10^{-7} Па$^{-1}$ in rock1 and rock3 domains, and 2.0 10^{-8} Па$^{-1}$ in rock2 domain.

(4) Thermal expansivity 1.75 10^{-2} °C^{-1}. This pparameter needed to explain relatively small pressure response to reinjection in the North and Central sites of the field.

(5) Double porosity» implementation needed to explain transient temperature and enthalpy decline data in geothermal reservoir (Fig. 13). Double porosity was implemented in all «rock1» domain elements except of the south-east sector (105, 111, FFF10, FFF 7, FFF 8, FFF 9) and except of the north-west segment (FFF22, FFF23, FFF24, FFF25, FFF26, FFF27, 146), and also «double porosity» was implemented in element 6 of the model. ONE-D option of the “double porosity” with average fracture spacing 162 m (700:4.3) used, two element matrix subgrid and fracture porosity 0.2 in all elements, except of the North site elements 141, 5, 142, 143, 144, 139, 140, 135, 145, 134, 11, E1, 8, 15, R1, 16, RE4, 10, RE3, RE7, 7, 14, RE5, 20, RE1, RE2, GK1, 125, 124, 106, RE6, FF32, 6, where 0.1 fracture porosity value was assigned.

Figs. 15 and 16 shows modeling temperature distributions and flows (>5 kg/s between elements) by 2000 year of the exploitation in the fracture media and matrix media, correspondingly.

Fig. 15 shows very clear significant temperature decline in fracture media (production zones) as a result of reinjection and cold water inflows in the North site of the field, while heat capacity of the matrix media was not used (Fig. 16). Matrix temperature 20-30 °C greater than fracture temperature, that mean low efficiency of the heat extraction in reservoir under 1964-2000 year exploitation conditions observed.

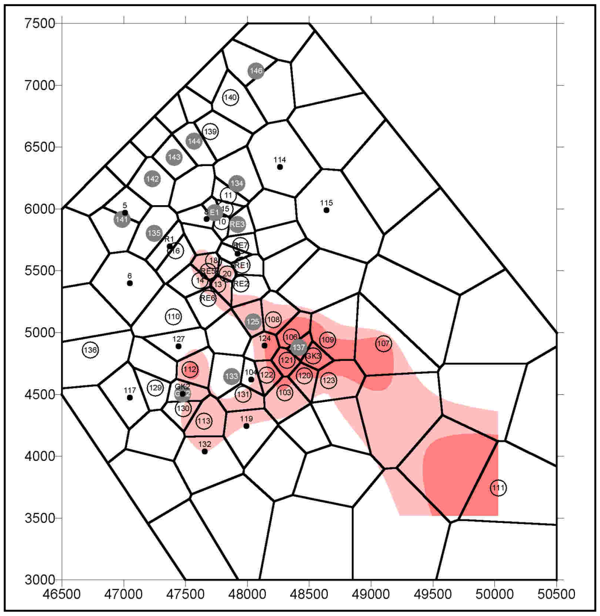

Figure 10. Pauzhetsky geothermal field: production wells – open circles, reinjection wells – large filled circles, monitoring wells – small black circles. Max observed temperature counters 195˙• and 200˙• (filled) are shown too.

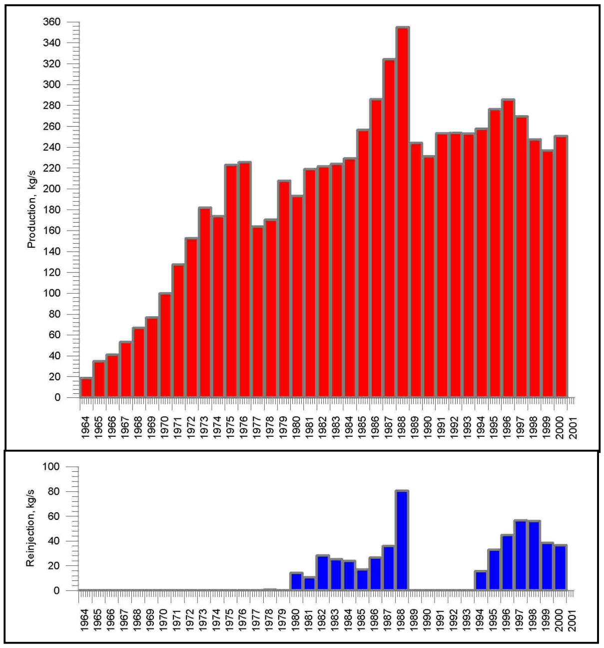

Figure 11. Pauzhetsky geothermal field exploitation 1964-2000: production (above) and reinjection (below) rates.

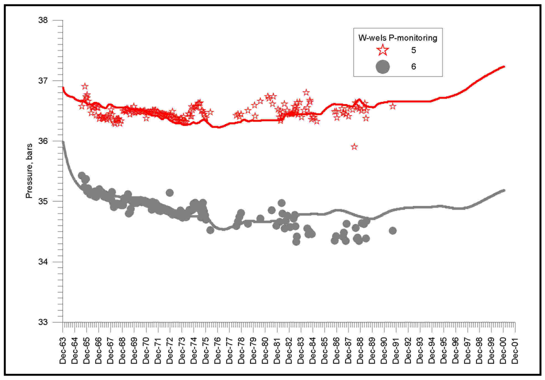

Figure 12. Modeling of the exploitation: pressure matches in wells 5 and 6: modeling results – continuos lines, temperature-logs-level based pressure estimates – filled circles.

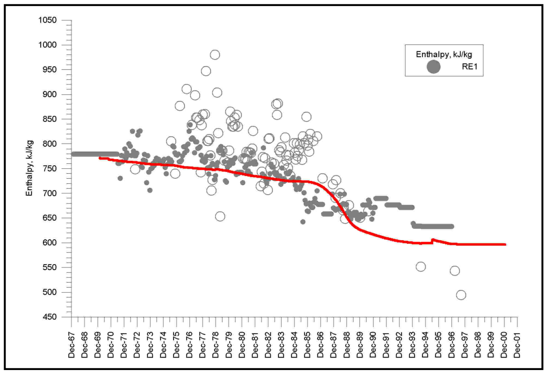

Figure 13. Modeling of the exploitation: enthalpy matches in well RE1: modeling results – continuos lines, direct enthalpy measurements – small filled circles, Na-K geothermometer enthalpy estimates – open circles.

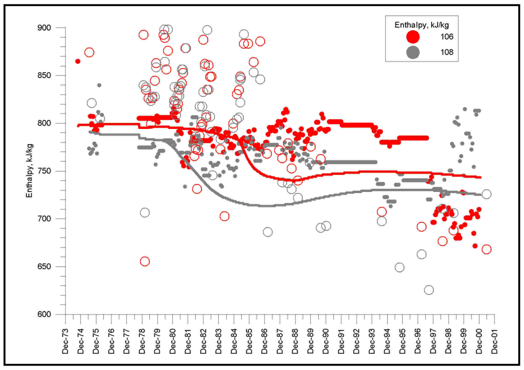

Figure 14. Modeling of the exploitation: enthalpy matches in wells 106 and 108: modeling results – continuos lines, direct enthalpy measurements – small filled circles, Na-K geothermometer enthalpy estimates – open circles.

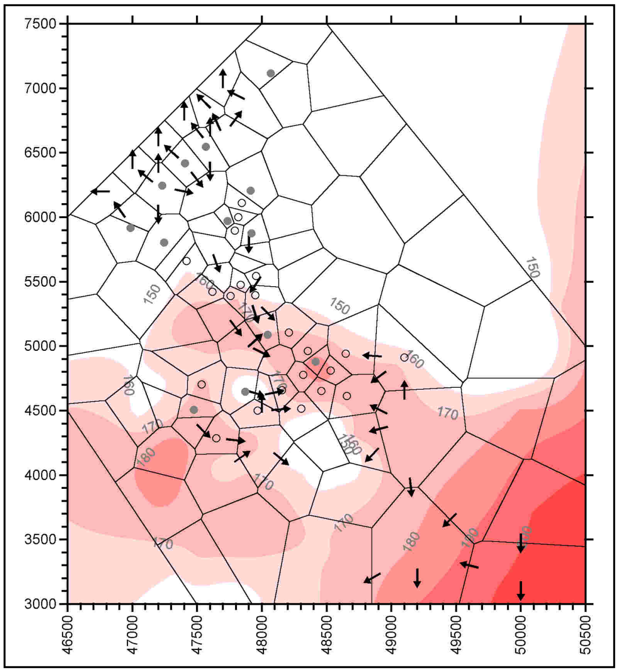

Figure 15. Exploitation model: temperature distribution and mass flows (>5 kg/s) by 2000 year in the "fracture" elements of the double-porosity media.

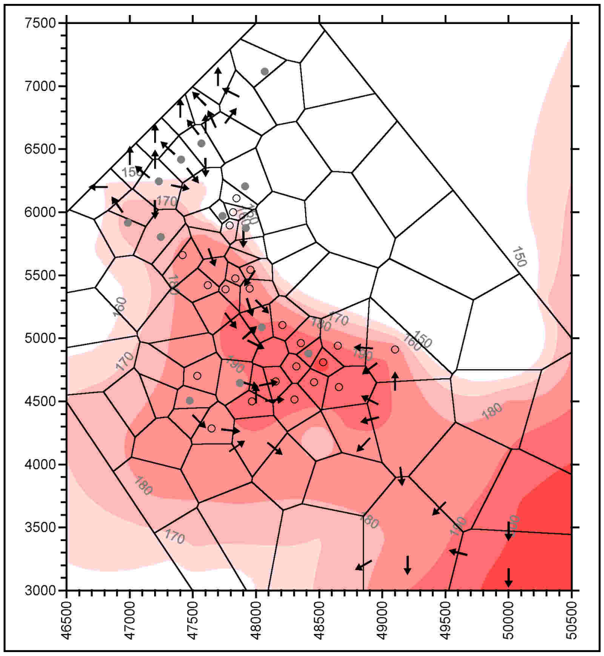

Figure 16. . Exploitation model: temperature distribution and mass flows (>5 kg/s) by 2000 year in the "matrix" elements of the double-porosity media.

20-YEAR FORECAST SCENARIOS

The calibrated model of the Pauzhetsky geothermal field was used to forecast different exploitation scenarios for the next 20 years of the exploitation.

Constant rate production scenario for 2001-2020 years exploitation period

Constant rate production (wells 103, 106, 108, 120, 121, 122, 123, GK3) were assigned in the model with rates corresponding to December 2000. The following sub-scenarios were analyzed in the model:

(1) Reinjection wells rates were assigned in the model corresponding to December 2000,

(2) Reinjection was stopped in the model since 2001 year,

(3) Reinjection was never assigned in the model et al, including 1964-2000 years and 2001 – 2020 years time periods.

Sub-scenario (1) shows steam production decline of the wells during 20 years exploitation period will be from 25.6 kg/s to 21.1 kg/s (17.8%). Sub-scenarios (2) and (3) analysis shows reinjection impact on the exploitation. If reinjection discontinue from 2001 year, then steam production decline during next 20 years exploitation period from 25.6 kg/s to 22.7 kg/s (11.3%). If no reinjection et al, then steam production rate decline to 21.9 kg/s (14.4%).

In general, the effect of the reinjection was found to be negative for wells of the North site (well RE-1 enthalpy drop shown in Fig. 13 as an example), but may be positive for some wells from Central site of the field (103, 120, 123). Basically, these Central site wells are in danger of gravitational cold water drop from south part of the field (due to structure geometry of the production layer, see Fig. 6), so pressure maintain in important there to avoid such gravitational instability.

Constant wellhewd pressure production scenario for 2001-2020 years exploitation period

The following equation implemented as a subroutine DEBIT in TOUGH2 (version of 1991 year code) to represent well (at the constant wellhead pressure) – reservoir interaction (A.Kiryukhin, 1992):

$$Q = PI * (P_r - P_b(WHP, Q, h, d)),$$

where Q – mass flowrate of the well; PI – well productivity index; P_r - reservoir pressure , P_b(WHP, Q, h, d) – pressure at production zone level, which depends of Q, flowing enthalpy h, wellhead pressure WHP and well casing program d (diameter vs depth). DEBIT used P_b(WHP, Q, h, d) tables, which were calculated in advance with HOLA wellbore simulator code (Fig. 17). Wells production indexes were estimated based on the tables above.

Production scenario include wells 106, 108, 121, 122 and G•3 at constant wellhead pressures and constant rate production from wells 103, 120 and 123, at level of December 2000). Two sub-scenarios were analyzed:

(1) Reinjection wells rates were assigned in the model with rates corresponding to December 2000,

(2) Reinjection was stopped in the model since 2001 year.

Fig. 18 shows steam production rate decline for wells (106, 108, 121, 122, GK3) from 18.3 to 16.7 kg/s (8.5 %) for “reinjection continue” sub-scenario, and from 18.3 to 17.3 kg/s (5.5 %) for reinjection “discontinue” sub-scenario.

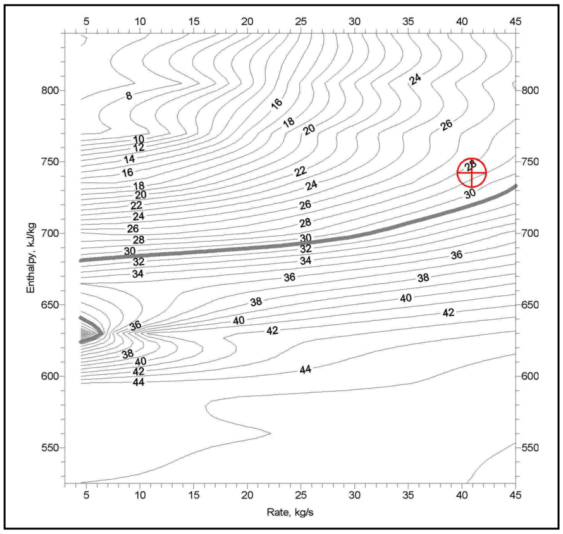

Figure 17. Estimated bottom hole pressure vs. enthalpy and rate of the well 106 at wellhead pressure 3.7 bars. ⊕ symbol - well (Q,h), thick line – reservoir pressure P_r at December 2000 conditions.

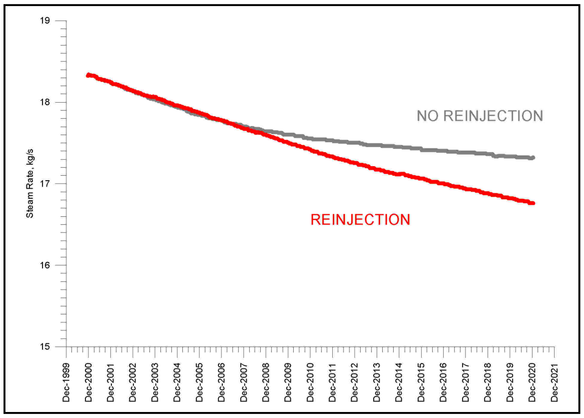

Figure 18. Total steam rate production 20-year forecast for wells 106, 108, 121, 122, and GK3.

CONCLUSIONS

Numerical model of the Pauzhetka geothermal field, Kamchatka, Russia was developed based on TOUGH2 code and HOLA wellbore simulator. Model was applied to 1964-2000 year data exploitation analysis and forecast two exploitation scenarios. The following results were obtained:

(1) Natural state modeling study was used to identify location, mass flowrate and enthalpy of the natural high temperature upflows as 204 kg/s and 830-875 kJ/kg (in total for the North site and Central site of the Pauzhetsky geothermal field).

(2) Modeling study of the 1964-2000 year exploitation confirm the «double porosity» behavior of the reservoir, which active volume estimated as 10 – 20 %. Mass fluid extraction rate over the natural high temperature upflow recharge and negative reinjection effect caused temperature and enthalpy decline in production zones. As a result of this North site was abandoned in 1997.

(3) Two basic scenarios for next 20 years exploitation were investigated and steam production rate (at 2.7 bars) forecast was done. If mass extraction and reinjection rate will maintain at December 2000 level, then total steam production decline from 25.6 kg/s to 21.1 kg/s (17.5%). If five of eight production wells (106, 108, 121, 122, GK3) will maintained at constant well head pressures at December 2000 level, then steam production from five wells will decline from 18.3 kg/s to 16.7 kg/s (8.5%).

(4) More greater mass extraction rates and increase of reinjection rate compare to existing load may cause more severe steam production drop in the Pauzhetsky geothermal field. Mass flow extraction rate at 200 kg/s seems to be an upper limit for Central site, high enthalpy exploitation wells are preferable. Additional exploration drilling is recommended at South-East site of the field, where 120 kg/s and 900 kJ/kg upflow suggested.

(5) The temperature logging in wells (5, 6, 8, P1, 115, 117, 119, 132 124) is recommended for more accurate lateral cold inflows estimations. High accuracy enthalpy-flow measurements of exploitation wells (103, 106, 108, 120, 121, 122, 123, ГК3) are extremly desired to explain measured and Na-K enthalpy non-convergence.

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