MODELING THE PAUZHETSKY GEOTHERMAL FIELD, KAMCHATKA, RUSSIA

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ABSTRACT

The forward TOUGH2 modeling study of the Pauzhetsky geothermal field (Kiryukhin and Yampolsky, 2004) was followed by an iTOUGH2 analysis to obtain more reliable reservoir parameter estimations. The model was automatically calibrated against (1) natural state and (2) production data. For the natural state modeling, calibration data include 68 points (2 natural discharge rates, 14 reservoir pressures at -250 m.a.s.l., and 52 reservoir vertically averaged temperatures). The different quality of the calibration points was expressed by specifying appropriate standard deviations. Preliminary estimates of the principal parameters are: (1) permeability k = 83 mD, and (2) an upflow rate Q_b = 46.5 kg/s.

For the modeling of the exploitation phase, calibration data include 60 datasets: enthalpies of the exploitation wells (10 data sets), pressures in monitoring wells (24 data sets), and temperatures in monitoring wells (26 data sets), with a total of 15,030 calibration points. The following parameters are estimated: (1) reservoir fracture porosity, (2) basement porosity, and (3) infiltration “window” permeabilities. Model calibration will be followed by an analysis of the sustainable capacity of the Pauzhetsky field.
Keywords: Pauzhetsky, Geothermal, Modeling, Exploitation, iTOUGH2.

INTRODUCTION

The Pauzhetsky geothermal field has been developed since 1966, when a 5 MWe power plant was put into operation. The first reservoir engineering study of this field conducted by Sugrobov (1965) revealed a liquid-dominated reservoir with layer type tuffs at 170-190°C, with hot springs discharges at 31 kg/s. The lumped parameter model by Sugrobov (1976) yielded 460 kg/s lateral, high-temperature outflow from the Kambalny ridge into the geothermal reservoir. However, the initial 10 years of the exploitation at 160-190 kg/s show gradual temperature decline and chloride dilution of the production wells located near the natural discharge area, so new exploration wells were drilled, and exploitation gradually shifted away from the natural discharge area until temperatures of 200-220°C were reached. Wells were drilled into a central upflow zone located 1.5-2.0 km southeast from the old production field (Yampolsky, 1976). The drop in temperatures and enthalpies continued, while total flow rate reached 220-260 kg/s between 1975 and 2005. The forward TOUGH2 modeling study of the field conducted by Kiryukhin and Yampolsky (2004) yielded the following estimates of the principal parameters: (1) An upflow rate of 220 kg/s with an enthalpy of 830-920 kJ/kg, (2) a permeability-thickness of 70 D·m in the central part of the field, and a compressibility of 5.0 10^{-7} Pa^{-1}, (3) a fracture spacing of 162 m and fracture/matrix ratio of 0.1 for the dual-porosity model, and (4) the existence of constant pressure boundaries.

The sustainable capacity of the Pauzhetsky field became a critical question for power plant reconstruction and new binary technology implementation, and a more detailed calibration study was performed. In this study, iTOUGH2 was used for parameter estimation. The current numerical model (mesh has 424 elements, 294 being active) represents a 3-layer system (caprock, reservoir of 500-m thickness, base rock) with an interior upflow zone and external constant pressure recharge-discharge boundaries.

CONCEPTUAL HYDROGEOLOGICAL MODEL

The Pauzhetsky geothermal field is situated inside the Pauzhetka volcano-tectonic depression (Fig.1). The oldest rocks penetrated by wells at 650-m depth are Miocene sandstones. Pauzhetka tuffs (N_2-Q_1) include welded tuffs, tuffaceous conglomerates, and psephitic tuffs. The caprock is represented by a 100-m thick layer of dacitic alevropelitic tuffs. Rhyolite and andesite-dacite extrusions (domes and ridges) of 0.01 to 8 km^2 size are common. The Dacite extrusion complex ($Q_{2\text{-}3}$), which is located inside the 190^{o}C zone, acts as a structural control for the temperature and permeability distribution. This complex is penetrated by wells 111, 124, 105, 101, 123, 107, 106, and 131 at depths more than 50 m. A graph of cumulative production rate per well vs. depth shows that most production occurs in the interval from 100 to 800 m depth, with a maximum rate of 23.2 kg/s. This interval includes the lower and middle parts of the Pauzhetka tuff formation (N_2-Q_1 pau$_{1,2}$) and Golyginsky Layer (N_2 gol). This is a clear indication of the layered structure of the permeability in the Pauzhetsky geothermal field. Integrated analysis of the field data shows the following reservoir characteristics:

(1) The Pauzhetsky reservoir is layered with an area of 2×2.5 km^2 and an average penetrated thickness of 505 m connected at the bottom with the hot water upflow.

(2) Well logging analysis show a double-porosity response of the reservoir, with a fracture volume fraction (FV) of 0.28 and an average fracture spacing (FS) of 105 m.

(3) Natural thermal discharges include dominant hot boiling springs discharge with a measured rate of 31 kg/s, and steaming grounds (Verkhnee and East with a total discharge rate of 0.7 MWt).

(4) Permeability-thickness kh and total production zones compressibility $C_t \cdot \phi \cdot h$ estimates based on multiwell flowtest semi-log analyses show a kh range from 35 to 94 D·m and $C_t \cdot \phi \cdot h = 9.0\ 10^{-6}$. Laboratory testing of reservoir rock samples (matrix) show a porosity up to 0.2 and a density of 1500 – 1800 kg/m^3 (Ladygin et al., 2000), and an average heat conductivity (dry conditions) of 1.6 W/m ^{o}C (Sugrobov and Yanovsky 1987).

(5) Initial reservoir pressure is 34.5-35.5 bars at -250 m.a.s.l., and tends to increase in south-easterly direction (North site of the field).

(6) The production reservoir temperature is 180 – 220 ^{o}C; the upflow zone is delineated by a temperature countour within the drilled part of the field.

(7) The chemical composition of the thermal fluid is characterized by Cl-Na and CO_2-N_2, with a dissolved solids content of 2.7 – 3.4 g/kg. Hydroisotopic (δD, δO_{18}) composition of the thermal fluids correspond to the Kurile Lake water – Kambalny Ridge cold springs range, which demonstrates their meteoric origin.

Based on the above data, the following hydrogeological conceptual model was assumed. Cold meteoric water infiltrates through open fractures at 5-6 km depth in a high-temperature zone above 250^{o}C (where remaining hot magma bodies are located), heats up and upflows. Upflows of high-temperature fluids with enthalpies of 950-1050 kJ/kg through the base and Miocene sandstone rocks to reach the volcanogenic-sedimentary basin, where layered production reservoir is located (see Fig. 1).

NUMERICAL MODEL SETUP

Grid Generation

The geothermal reservoir was represented in the model as a three-layer system that covers the existing well field. This model includes: (1) a middle layer representing the hydrothermal reservoir at -250 m.a.s.l. with an average thickness of 500 m; (2) an upper layer caprock with "hydraulic windows" allowing for natural discharge (from the top of the hydrothermal reservoir at 0 m.a.s.l. to the land surface); and (3) a base layer hosted upflow plumbing system zone with an average thickness 500 m. The preprocessor A-mesh was used for grid generation. The total number of elements is 424, including 294 active elements.

Boundary Conditions

Mass sources were introduced in the model where the natural high-temperature upflows were assumed to occur, with enthalpies in the range 950-1050 kJ/kg corresponding to liquid water temperatures of 220-240 ^{o}C. Heat sources were assigned at the bottom of the model layer to reproduce background conductive heat flow (0.063 W/m^{2}). Lateral no-flow boundaries were assigned. Discharge conditions were assigned through additional inactive elements CR1 1, C135 1, C 5, and C142 of the caprock "hydraulic window" with the centers at the land surface, constant atmospheric pressure, and 100^{o}C discharge temperature. These elements were vertically connected to elements R 1, 135, 5 and 142 of the mid-layer hydrothermal reservoir, where most of the natural discharge occurs in the form of hot springs. Additional natural discharge elements (CC27 / FF27) were used to represent hidden natural discharge zones revealed by Sugrobov (1965). Conductive heat loss from the hydrothermal reservoir to the caprock was modeled by specifying inactive boundary elements with a constant temperature of 5^{o}C.

Zonation and Rock Properties

The model domain was subdivided into several zones to represent major discharge zones (referred to as "hydraulic windows" in the caprock). The mid-layer hydrothermal reservoir was subdivided into a central part (ROCK1), boundary parts (ROCK4), and an internal, relatively impermeable domain (ROCK2). The base layer was divided into the upflow zone (BASE2) and host rock (BASE1). The caprock and hydrothermal reservoir rock were assigned a porosity of 0.20, a density of 1500 – 1800 kg/m^{3} (except for the boundary domains, where rock density was 2300 kg/m^{3} assigned), and a thermal conductivity (wet) of 1.8 W/m ^{o}C. Base rocks were assigned a porosity of 0.02, a density of 2300 – 2800 kg/m^{3}, and a thermal conductivity of 2.1 W/m ^{o}C. Specific heat was 1000 kJ/kg ^{o}C throughout the model domain.

Double-Porosity Conversion

Mid-layer elements were MINC-processed to introduce double-porosity conditions with a fracture spacing of 105 m and a specific fracture volume of 0.3.

NATURAL STATE MODEL CALIBRATION

Model Parameterization

Calibration points for natural state modeling include: (1) Vertically averaged temperatures in the mid-layer hydrothermal reservoir (52 T-points); (2) Pressures calculated at -250 m.a.s.l. (based on level and temperature logs in wells) (14 P-points); (3) Natural discharge rates (2 values). Estimated parameters include mass flow rates assigned at the bottom of the base, and the mid-layer hydrothermal reservoir fracture permeability distribution.

iTOUGH2 Parameter Estimates and Error Analysis

The Levenberg-Marquardt algorithm implemented in iTOUGH2 was used to minimize the weighted least-squares objective function, which is a measure of the discrepancy between modeled and observed data at the calibration points. The calibration against temperature data in the central part indicated that it is very unlikely that an open lateral boundary exists. Therefore, the lateral boundaries were closed, and the following estimates were obtained (run #NS7-4k6): permeabilities of 83 mD and total upflow rate of 46.5 kg/s (with enthalpy 950-1050 kJ/kg). Estimated parameters show negative correlation. The range of 95% confidence is reasonably estimated as [76 mD, 93 mD] for permeability, and [41.6 kg/s, 51.4 kg/s] for upflow rate.

The match between the model and measured temperatures and pressures (run #NS7-4k6) shows standard deviation of temperature residuals is 7.5^{o}C, standard deviation of the pressure residuals is 0.5 bars; the discharge rate was matched to 6% of the observed value. The relatively large pressure deviations are considered acceptable because of the poor quality of the pressure data.

Comparison of iTOUGH2 and Previous Estimates

We compared the iTOUGH2 estimates with previous assessments by Kiryukhin and Yampolsky (2004). Permeability estimates agree reasonable well with previously obtained values of 100 mD. However, the upflow rate estimated by iTOUGH2 is 46.5 kg/s, which is significantly less than previous estimates of 224 kg/s. This is most likely a result of (1) the change in lateral boundary conditions, (2) the fact that remote temperature data were not included in the previous, manual calibration, which was restricted to matching the 190^{o}C isotherm only.

CALIBRATION OF EXPLOITATION MODEL (1966-2005)

Model Parameterization

Calibration data sets for exploitation modeling include: (1) Monthly averaged enthalpies in exploitation wells (20, RE1, 106, 108, 120, 121, 122, 123, ГК3, 103) (10 E-datasets), (2) monthly averaged pressures at -250 m.a.s.l. (based on level and temperature logs in wells) (24 P-datasets), and (3) monthly averaged temperatures in the mid-layer hydrothermal reservoir (26 T-datasets). The total number of calibration points used was 15,030. Estimated parameters include (1) effective reservoir fluid and mass capacity, which defined by fracture porosity (ϕ_f), (2) upflow rate from basement induced by exploitation, which defined by basement porosity (ϕ_B), (3) meteoric water infiltration inside of the geothermal reservoir, which defined by three additional "hydraulic windows" introduced in the model's upper-layer caprock and corresponding permeabilities: k_N (North site caprock permeability), k_W (West site caprock permeability) and k_E (East site caprock permeability. Reservoir and basement compressibility were assigned as 2 10^{-6} Pa^{-1}, having in the mind strong (-1) negative correlation of those parameter with porosities.

iTOUGH2 Parameter Estimations and Error Analysis

Exploitation was modeled by specifying monthly averaged production and reinjection rates (January 1965 – December 2005) (Fig. 2), using the natural state temperature and pressure distribution (run #NS7-4k6) as initial conditions. The following estimates were found (run #7YC):

Table 1: Parameter Estimates and Their Uncertainties

Estimated parameter	Value	95% confidence interval
ϕ_f	0.094	0.090-0.098
ϕ_B	0.045	0.037-0.053
k_N, mD	145	129-162
k_W, mD	490	371-645
k_E, mD	11	10.0-11.7

Run #7YC show the mean residual of enthalpies at the production wells, temperature, and pressure of 36.7 kJ/kg, 12°C, and 0.42 bars, respectively. Figs. 3 show examples of the enthalpy match in well RE1. The following measures will likely improve the matches: (1) Recent installations of orifice meters and trays for separate water will yield additional high quality data for production wells, (2) reservoir pressure monitoring data in the central part of the field strongly required, in order to get them capillary tubing system installation needed. Additional model improvements may be obtained through more accurate assignment of the infiltration domains.

The most sensitive model parameters are reservoir fracture porosity, the P-datasets from the center wells, the T-datasets from remote wells and and E-datasets from wells under cooling conditions.

The estimated parameters (reservoir and basement porosities and "hydraulic windows" permeabilities) were relatively weakly correlated (less than 0.2, and greater -0.5), helping to reduce the estimation uncertainty (see Table 1 above).

HEAT, MASS AND CHEMICAL BALANCES OF THE PAUZHETSKY HYDROTHERMAL RESERVOIR

Heat and mass balances can be derived from the simulations (run #7Y6) to understand sources of exploitation reserves.

The components of the mass flows balance by Nov. 2005 are the following:

F1. Natural upflow rate: +46.5 kg/s;

F2. Additional upflow rate, induced by exploitation: +70.5 kg/s;

F4. Meteoric water infiltration: +85.4 kg/s;

F5. Separate reinjection: +23.8 kg/s.

F6. Hydrothermal reservoir fluid capacity (calculated from balance): +62 kg/s;

F7. Flow rate from exploitation wells (RE1,103, 106, 108, 120, 121, 122, 123, GK3): -269.3 kg/s;

F8. Fluid discharge from reservoir: -18.9 kg/s.

The components of the heat flow balance by Nov. 2005 are the following:

HF1. Natural upflow: +46.5 MW;

HF2. Additional heat upflow rate, induced by exploitation: +71.9 MW

HF3. Conduction heat flow from base rock: +1.7 MW;

HF4. Conductive heat losses through reservoir roof: -0.5 MW;

HF5. Separate reinjection: +12.0 MW;

HF6. Hydrothermal reservoir heat storage capacity (calculated from balance): +100.8 MW;

HF7. Heat flow rate from exploitation wells (RE1,103, 106, 108, 120, 121, 122, 123, GK3): -214 MW;

HF8. Convective heat discharge from reservoir: -18.9 MW;

Chemical balance based on chloride may be calculated, if parental fluid Cl^- concentration (C1=1600 ppm (Pauzhetka et al., 1965) is assumed to be equal to the additional upflow (induced by exploitation) fluid concentration C2 and to the reservoir fluid chloride concentration C3, so that C1=C2=C3=1600 kg/kg; meteoric chloride concentration C4=10 ppm; the chloride concentration of the reinjected water is C5, and the remaining springs discharge chloride concentrations C8 are assumed to be C5=C8=1300 ppm.

Based on mass balances above, the following chloride mass flows derived:

CF1. Chloride natural upflow rate:

CF1=+F1*C1=+74.4 g/s.

CF2. Additional chloride upflow rate, induced by exploitation: CF2=+F2*C2=+112.8 g/s.

CF4. Meteoric water chloride infiltration:

CF4 = +F4*C4=+1 g/s.

CF5. Chloride in separate reinjection: CF5=+F5*C5= +31 g/s.

CF6. Chloride from hydrothermal reservoir fluid capacity: CF6=+F6*C6=+99.2 g/s.

CF8. Chloride discharge from reservoir:

CF8=-C8*F8=-24.6 g/s.

Hence, chloride mass flow from exploitation wells CF7 (chloride mass flow from exploiataion wells) can estimated as: CF7=CF1+CF2+CF3+CF4+CF5+CF6+CF8=293.8 g/s.

Actual chloride mass flow from exploitation wells (RE1,103, 106, 108, 120, 121, 122, 123, GK3) are estimated based on a chemical analysis of extracted fluids and well flowrates as 260-271 g/s, which are within 8-11% of the previous estimates, confirming model calibration results.

CONCLUSIONS

(1) The Pauzhetsky geothermal reservoir was represented in the model as a three-layer system of the existing well field. This model includes: (1) Mid-layer hydrothermal reservoir at -250 m.a.s.l. with an average thickness of 500 m; (2) Upper layer caprock with “hydraulic windows” representing natural discharge zones; (3) Base layer with the upflow zone of an average thickness of 500 m.

(2) For the iTOUGH2 natural state modeling, calibration data include 68 points (2 natural discharge rates, 14 reservoir pressures at -250 m.a.s.l., 52 reservoir vertically averaged temperatures). The different quality of the calibration points was expressed by specifying appropriate standard deviations. Estimates of the following parameters were obtained: (1) permeability, and (2) upflow rate.

(3) For the modeling of the exploitation phase using iTOUGH2, calibration data include 60 datasets: enthalpies of the exploitation wells (10 data sets), pressures in monitoring wells (24 data sets), and temperatures in monitoring wells (26 data sets), for a total of 15,030 calibration records. Estimation of the following principal parameters was performed: (1) reservoir fracture porosity, which responsible for effective heat and mass capacity of the reservoir layer, (2) basement porosity, which responsible for additional upflow induced by exploitation, (3) permeabilities of infiltration windows. Reasonable matches in the model calibration points obtained. Heat and mass balances derived from the model are used to understand the sources of exploitation reserves. Chemical balances were calculated to corroborate the calibration results.

(4) Model calibration is still on going and will be followed by an analysis of the sustainable capacity of the Pauzhetsky field.

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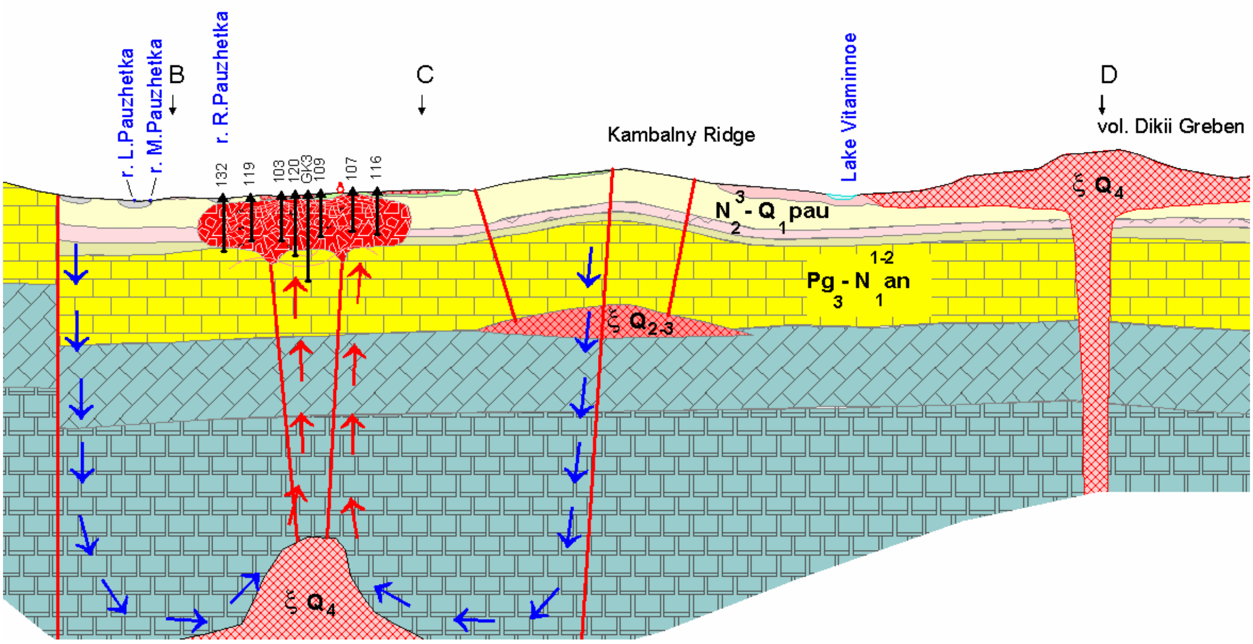

Fig. 1. Conceptual model of the Pauzhetsky geothermal field.

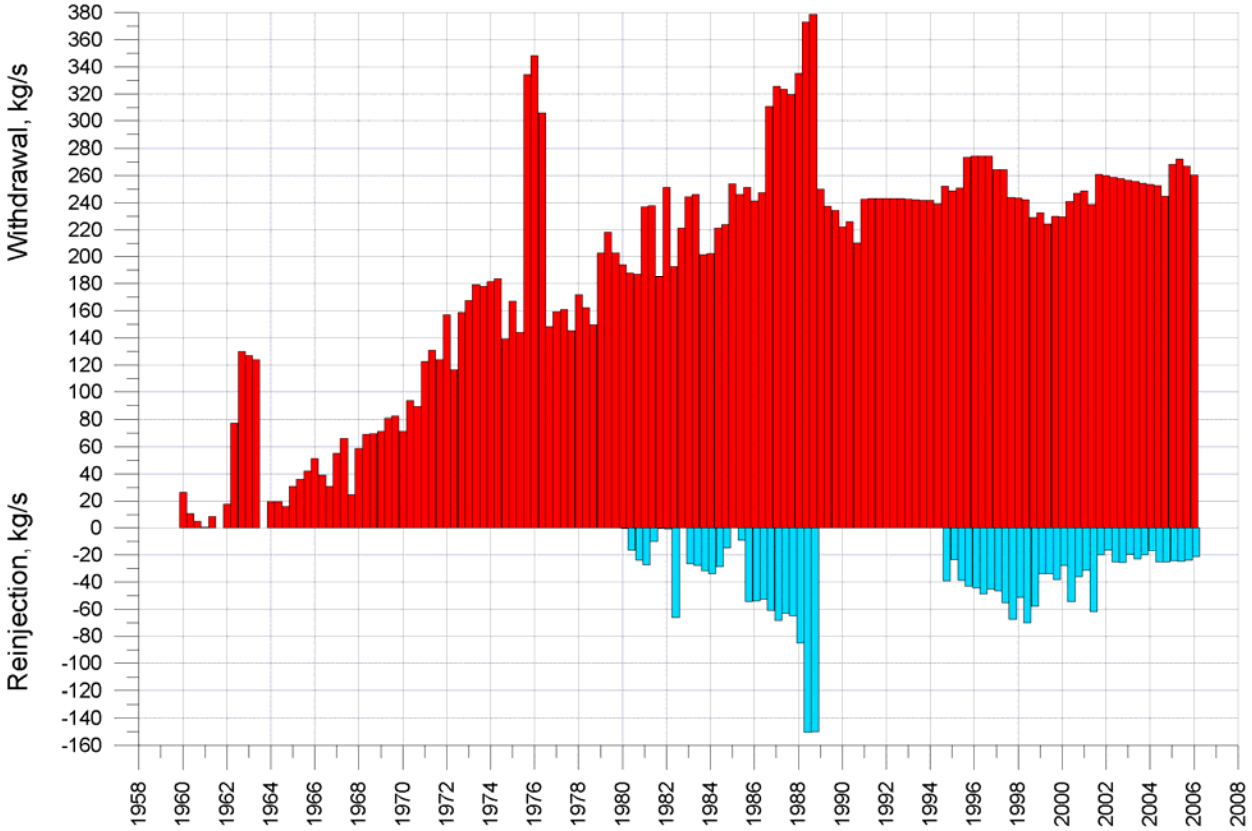

Fig. 2 Extraction (above) and reinjection (below) rates during of exploitation 1965-2005.

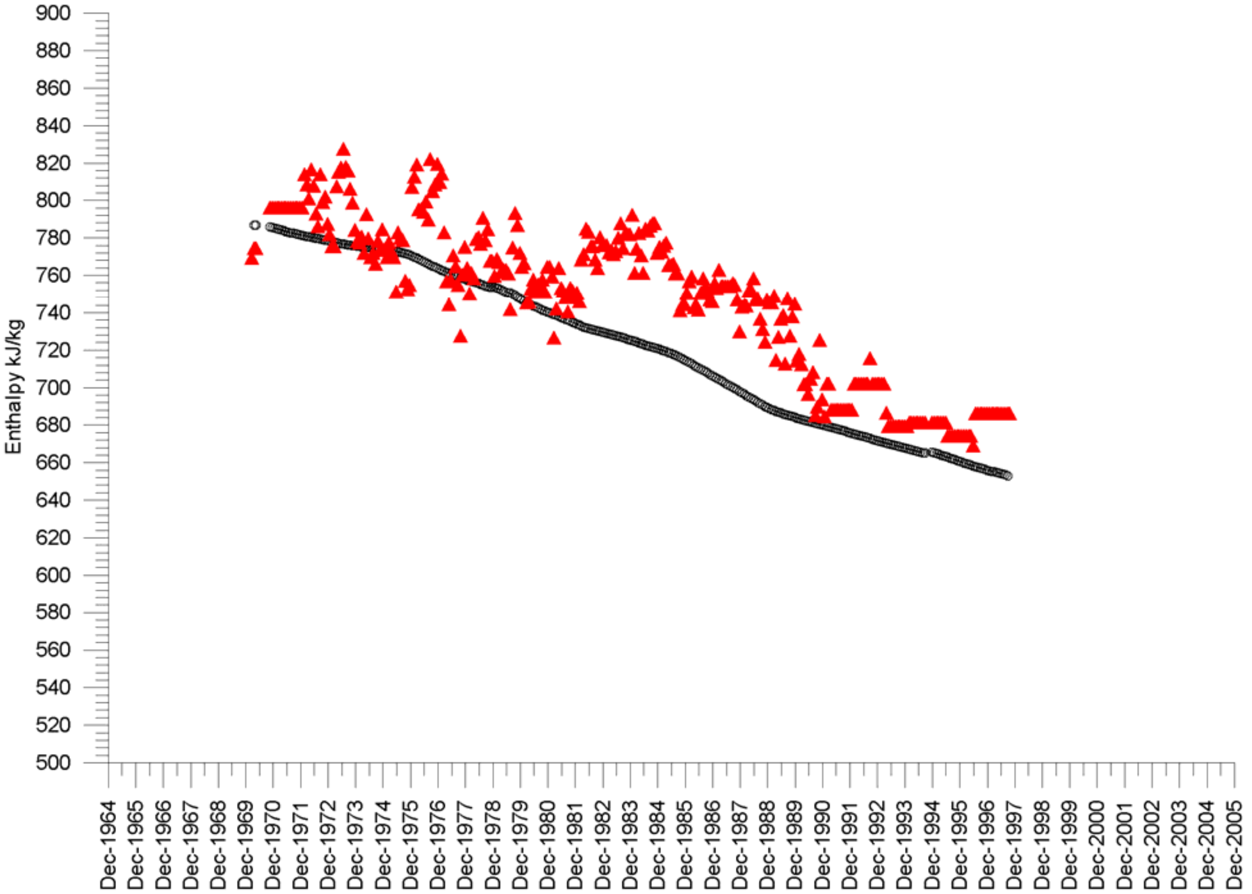

Fig.3 Calibration of the exploitation model: enthalpy match in well RE1 (triangles – observations, line - model).