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GEOTHERMAL WATERS REINJECTION
INTO SANDSTONES AND CARBONATE RESERVOIR ROCKS

1. INTRODUCTION

Exploitation and reinjection of geothermal waters after partial recuperation of their enthalpy has become a world's common practice since the 1970s. Recently the "used" thermal waters have been usually injected to the pore- and fracture-type collectors. There are two reasons for which injection methods are applied in low and high enthalpy geothermal systems [4]. Firstly, to maintain the formation pressure (especially important for high enthalpy resources), and secondly, because of environmental problems with discharging great amounts of saline waters (low enthalpy resources). The theoretical bases of maintaining the pressure can be found in, e.g. Lippman *et al*. [8], Bodvarson *et al*. [3]. Two types of reservoir collectors can be encountered in the Palaeozoic and Mesozoic formation in the Polish Lowland: pore- and fracture-type collectors. Physical phenomena related with the injection of fluids to the pore- and fracture-type medium can be divided into hydrodynamic (re-pressure and fracturing effects) and thermodynamic phenomena connected with a change of temperature and chemical composition of fluid. Both these effects may influence each other. It follows from the world' and Poland's industrial practice that injection of chilled water to the fracture-type collectors can be done without much problem (except for determining the front of cool water to the pumping well.) Owing to their structure, pore-type collectors are low-permeability collectors. According to the German and French data, the minimum permeability of a pore-type collector, fit for thermal waters injection, is assumed to be 500 md [11] or 100 md [1, 14].

2. HYDRODYNAMIC EFFECTS ACCOMPANYING FLUIDS INJECTION TO POROUS AND FRACTURED MEDIA

In the course of injection procedure, formation pressure needs repression. The magnitude of pressure depends on the hydraulic conductivity of the bed (T or kh), state of the near-well zone (skin effect) and viscosity of the injected water, see Figure 1.

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The flow pattern of a single doublet can be easily examined on the basis of the following assumptions:

- the producing aquifer is horizontal, of constant thickness h and of infinite lateral extension;
- the porous medium is homogeneous and isotropic with constant permeability and porosity;
- flow is assumed to be steady since the duration of transient flow is short compared with the duration of studied problem;
- bedrock and caprock are impervious and heat transfer with the reservoir is neglected;
- the two wells set at a distance D are working at constant flow rate Q, positive for the injector, negative for the producer;
- differences in viscosity between injected water and reservoir water are neglected;
- there is no regional flow in the aquifer.

Assuming that the flow can be described by Darcy's law and taking advantage of superposition principle in space, the pressure variation over the aquifer can be expressed by using the logarithmic approximation of exponential-integral solution of diffusivity equation. With reference to a cartesian plane in which the producer and injector are located at $(-a, 0)$ and $(+a, 0)$, respectively, the reservoir pressure is given by [2]

$$p(x, y) = p_i + \frac{q\mu}{4\pi k h} \ln \frac{(x + a)^2 + y^2}{(x - a)^2 + y^2} \tag{1}$$

where:

$$
\begin{aligned}
k &\quad-\quad \text{permeability,} \\
m &\quad-\quad \text{dynamic viscosity,} \\
w &\quad-\quad \text{rate,} \\
p &\quad-\quad \text{pressure,} \\
a, x, y &\quad-\quad \text{coordinates.}
\end{aligned}
$$

Equation (1) shows that the lines of equal drawdown or build-up dP are circles, so that the rectangle delimiting the area outside which the reservoir pressure change is less than dP can be easily computed.

Equation (1) is also used to calculate the pressure drawdown at the producing well of radius r_{wb} by considering the corresponding co-ordinates $x = a + r_{wb}$ and $y = 0$. Considering also that $d \gg r_{wb}$ and thus $2a + r_{wb} \approx d$, the equation becomes

$$p_{wb} - p_i = \frac{q\mu}{4\pi k h} \ln \left(\frac{d}{r_{wb}} \right) \tag{2}$$

where:

$$
\begin{aligned}
p_{wb} &\quad-\quad \text{downhole pressure,} \\
p_i &\quad-\quad \text{initial pressure,} \\
r_{wb} &\quad-\quad \text{wellbore radius.}
\end{aligned}
$$

Apparent well radius is calculated using equation

$$r_{wb} = r_w e^{-S} \tag{3}$$

where S – skin effect.

Slightly different form may be μ characterizing the high rate injection process, where rate skin depended (Dq) is included into overall equation as

$$S = S' + Dq \qquad (4)$$

we can obtain

$$\Delta p = \frac{q\mu}{4\pi k\,h}\left(\ln\left(\frac{d}{r_{wb}}\right) + S'\right)\cdot q + D\frac{\mu}{2\pi k\,h}q^2 \qquad (5)$$

These additional pressure drop/ repression may be observed in the Figure 1 near wells. The estimated depression/repression may be frequently affected by chemical water/rock/ well interaction.
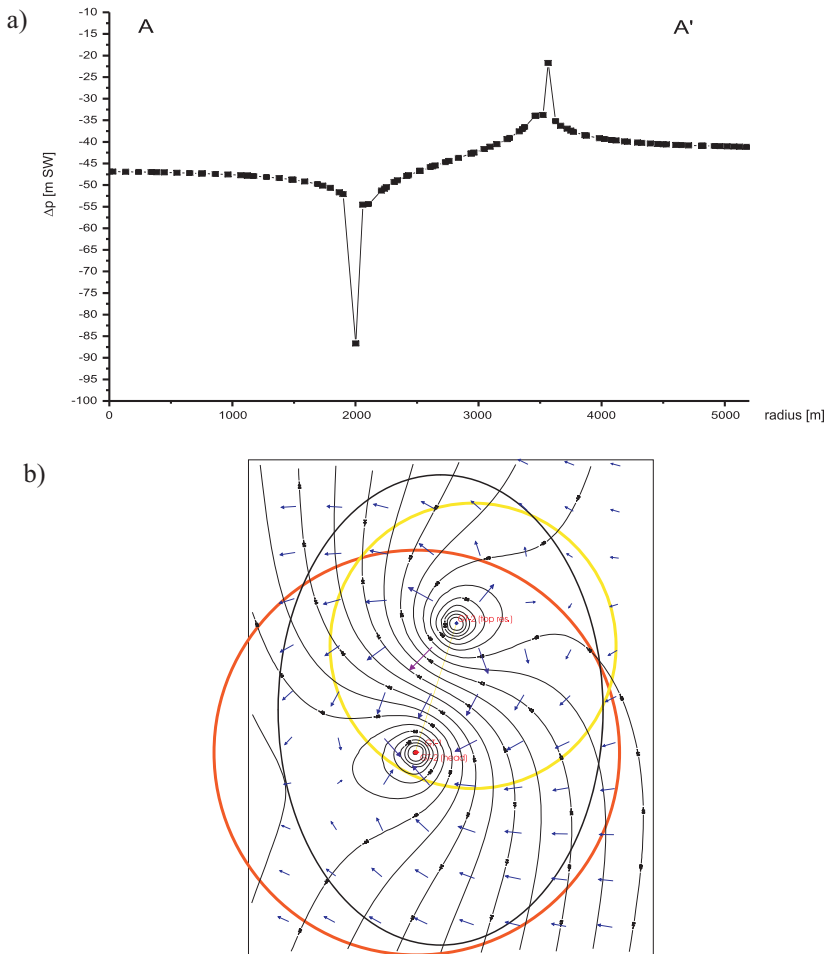

Fig. 1. Repression in a geothermal reservoir in doublet system: a) re-pressure and depression in wells; b) distribution of pressures in the reservoir

3. CHEMICAL & THERMODYNAMIC EFFECTS ACCOMPANYING INJECTION OF FLUIDS TO THE POROUS MEDIA

Exploitation may be accompanied by an additional drop (owing to fracturing) or additional increase of injection pressure. The latter may be caused by one or more factors [5, 6, 13, 15]:
– Filling up the reservoir in the case of trap-type deposits (e.g., in Paleozoic formations).
– Swelling of clayey minerals and falling off the porous space walls.
– Movement of solids from the deposit induced by the dissolving rock-binder; these solids close up the pore canals, thus reducing rock permeability.
– Presence of "suspended" solids in water, which close up the pores and reduce the permeability, thus leading to complete or partial loss of injectivity.

The first factor is rarely responsible for the loss of injectivity in a typical geothermal deposit. The remaining ones need additional comments:

Swelling of clayey minerals

Each clayey mineral reacts with new water differently. The degree of swelling of clayey minerals is a function of, e.g. ionic strength, pH of water, presence of organic polar compounds [15].

Swelling and liberation of clayey minerals

Clayey minerals present in a porous space may cause a considerable reduction of permeability for a couple of reasons:
– swelling of clayey mineral solids,
– movement of clayey mineral solids.

The extent of permeability reduction mainly depends on:
– number of clayey solids,
– type of solids,
– intensity of ionic phenomena,
– magnitude of pore canals (hydraulic radius).

The swelling and dislocation of clayey solids mainly results from a disturbed ionic balance in the porous spaces. Exploitation and cooling of thermal water in the heat recovery systems disturbs the ionic balance. Injection of cool water affects the ionic balance in porous spaces saturated with reservoir water, thus triggering out the process in clayey minerals.

Swelling of clayey minerals results from absorption of water particles by the crystalline network. As a consequence, the clayey mineral solids considerably increase their volume and choke the pore canals.

The swelling of clayey minerals may also result in the liberation of non-swelling clayey minerals, and consequently, choking of small pores and canals with the migrating solids. The migrating clayey mineral solids are severed (liberated) from the rock mass skeleton and diffused in the reservoir fluid filling up the porous space. The solids are transported with the filtering fluid (water) till the moment they are stopped in the canal contractions.

Three types of mechanisms of permeability reduction caused by clayey minerals can be distinguished:

1) migrating solids choke canal contractions,
2) swelling of clayey minerals,
3) migration of solids caused by swelling.

Formation and deposition of insoluble material in a deposit

Two mechanisms responsible for the formation and deposition of insoluble materials can be distinguished [15]:

1) Reaction of injected and reservoir waters, forming precipitations [5].
2) Retarded reaction of injected water, also resulting in a formation of solids.

Pore canals are curvilinear and irregular in shape. Particles from the deposit (fragments of minerals, crystals, clays etc.) may be loosely cemented with the pore channel walls. Each change disturbing the binding structure of the porous medium may also initiate a movement of solids in the canal (from the well towards the external borders of the deposit) till the moment it encounters an obstacle, e.g. a contraction of a pore channel.

Suspended solids

In contrast to a real solution of injected water, the precipitated solids are treated as „suspended" solids. Three types of "suspended" solids are usually mentioned: dispergead oil, clay, mud, sand, alga, deposition products, corrosion products (iron sulfide, iron hydroxide), bacteria, bacterial activity products, incompatible chemical. A classical division of "suspended" solids into organic and inorganic is more commonly substituted by a division into: adherent particles, non-adherent particles, particles potentially adherent, and potentially non-adherent.

Sources of solids precipitation in water

The main sources of solids precipitation are assumed to be the following:
– Sanding up processes in a production well.
– Overdosage of chemicals.
– Incompatibility of injected and source waters.
– Access of air to a closed system, causing precipitation of iron hydrogen and anaerobic bacteria.
– Flux of incompatible water from other formation, e.g. Liassic/Creataceous.
– Flocculation of particles behind the filtering system.
– Leaky filters.

The following problems related to the presence of precipitated solids are usually enumerated:

1) Precipitated solids may settle down inside the pumping system.
2) Precipitated solids may choke the pore canals, leading to reduced permeability.
3) Owing to a retarded reaction, they may form an additional impermeable filter in the reservoir after deposition.

4. PROBLEMS RELATED TO SCALING

The basic cause of scaling is a drop of pressure and/or temperature caused by natural production/injection processes. The aim of anti-scaling procedures may be the following [12]:

– Reduce production – the drop of pressure in this method is too low to trigger out mineral deposition processes.
– Injection of trace inhibitors on the well head.
– Injection of trace inhibitors downhole through an additional small-diameter assembly.
– Injection of inhibitor to the production horizon to enable its slow dissolution in the produced water.

The first method – limitation of production – is generally of little use. The second one prevents calcite scaling in the surface system, but does not protect against scaling in the casing or production pipes. The third method is technically correct but expensive. The last solution enables protection of the production pipes and surface assemblies in near well zone.

5. CORROSION

The newest solutions employ fiber glass pipes instead of their steel counterparts. For technical and economic reasons, also carbon steel and stainless steel are used for making the casing and pumping pipes. High temperature as well as high solids and CO_2 content in geothermal wells create a considerable corrosion hazard. The downhole part of the pipes is observed to be devoid of scale and actively corroded by the aggressive agents (Fig. 2).
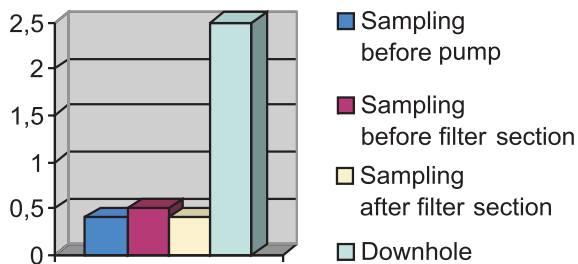

Fig. 2. Suspended particles concentration in injection process [9] [mg/kg]

6. INJECTION OF "USED" WATER TO THE PORE-TYPE COLLECTOR

The requirements set before water injected to a well usually guarantee a separation of 95% of particles > 5 μm and 100% of particles > 10 μm. Injection of water with a high content of suspended solids is frequently a basic cause of the loss of injectivity of a reservoir.

7. CONCLUSIONS

1) When injection is planed into carbonate – high naturally fractured rock – no special requirements are needed for quality of reinjected water.

2) Artificial fracturing of low permeability sandstone rock should be considered if average permeability is in the range 10–100 md. In case of doublet geothermal exploitation special procedure for limited range of fractured zone should be used.

3) The quality of waters would require special treatments – to reduce corrosion, to filter out suspended solids, to remove dissolved minerals (TDS), or to inhibit so-called scaling of well casings which would gradually inhibit flow; reinjection of oxidized water into the reservoir should be avoided.

4) Decline of permeability during injection of chemically unchanged thermal water is not caused by precipitation but by release and choking of small particles, probably feldspars and quartz splinters [7].

5) Special care must be taken with high colloidal Fe content waters [7, 10] strong permeability decrease arises during injection of brines with high amounts of colloidal Fe hydroxide even with water filtered to 10 and 3 μm and a permeability reduction is caused by formation of a filter cake. The permeability decrease depends on particle size and concentration, pore throat size and flow rate; colloidal iron is very small particles of oxidized iron suspended in the water. They are usually bound together with other substances.

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