

Key Technologies On Geothermal Water Reinjection Of Sandstone Porous Aquifers: A Case Study Of Dezhou Geothermal Reservoir In Northern China

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ABSTRACT

In accordance with the renewability of geothermal water, the geothermal systems in Northern China are divided into three types: open system, closed system, and weakly open system. In terms of closed geothermal systems, geothermal waters do not have a relationship with the modern water cycle. Due to no renewable recharge from modern water cycle in closed systems, the water levels are decreasing continuously in response to geothermal production. So, it is essential to study the sustainable yield of sandstone aquifers in northern China. Three reinjection experiments in sandstone aquifers of the Neogene Guantao Formation, which is widely distributed in Northern China Plain, have been successfully conducted in Pingyuan County, Dezhou City, Shandong Province, China.

The distance between the production and reinjection wells is 232 m, the depth to sandstone porous aquifer is 1130.70~1393.30 m, and the TDS of geothermal water is 5221.8 mg/l. The experiment has continued for 3 years, with the largest reinjection rate of 70 m³/h, accompanying a water level increase in the reinjection well of 28.65 m, and a water level increase in the production well of 3.55 m. This paper describes the geological conditions of the experiment site, and mainly explores the technical solutions for rapid aquifer clogging, which often accompanies sandstone aquifer reinjection. It involves reinjection well drilling techniques, filtering, oxygen free and re-pumping the reinjection well for 7 days.

1. Introduction

For the purpose of increasing the reinjection rate for sandstone aquifers, three reinjection experiments have been conducted in Pingyuan County, Dezhou City, Shandong Province, China, from 2012 to 2015.

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Due to heavy development and very limited recharge, fast pressure (water level) drawdown occurred in most of the sandstone porous aquifers. For instance, the water level depth decreased from 56 m to 68.5 m from Sep. 2012 to Sep. 2013 in Xian University of Armed Police with an annual drawdown of 12.5 m; and the artesian height decreased from 28 m to 6 m from Sep. 2012 to Sep. 2013 in 795 Factory of Xianyang with an annual drawdown of 22 m. Both of the wells are located in Xi'an-Xianyang Geothermal Reservoir, Guanzhong Basin, Shanxi Province. In Sep. 2013, the biggest water level drawdown occurred in Xijing Company of Electrical Equipment, reached to 295.7m from the artesian height of 127 m to water level depth of 168.7 m.

Neogene Guantao Formation is the main development and utilization reservoir in Binhai New Area of Tianjin, North China Sedimentary Basin (Figure 1). The reservoir pressure has dropped dramatically in recent years. Now the static water level depth is 90~114m, with the maximum dynamic water level depth of more than 146 m and the largest annual drawdown of 6.5m/yr (Lin, 2015).

Reinjection is a very important part of any geothermal development and it may become the key factor in the success or failure of the field (Rivera Diaz *et al.*, 2015). Obviously, it is essential to reinject to counteract fast pressure (water level) drawdown induced by heavy development. Reinjection allows for more thermal energy to be extracted from reservoir rocks which enlarges production capacity. It also decreases the disposal of geothermal tail fluid after space heating which could lead to thermal and chemical pollution. Meanwhile, reinjection can also mitigate land subsidence and be used to maintain geothermal manifestations (artesian wells, natural hot springs). But due to scaling, clogging and corrosion, the reinjection rate decreases dramatically in sandstone aquifers.

2. Geologic And Hydrogeological Setting

The Dezhou geothermal reservoir is located in the alluvial plain dominated by the Yellow River, which is within the North China Sedimentary Basin (Figure 1). Dezhou, a city situated in the northwest part of Shandong Province, has a population of 300,000 and lies approximately in the center of the geothermal area.



Figure 1: Location of the Dezhou Geothermal Field, China (Kang, 2013)

The Dezhou geothermal reservoir is a low-temperature sedimentary reservoir yielding water with a temperature between 46 and 58°C. 254 wells have been drilled into the reservoir since 1997. The emphasis on geothermal development has been in the area of direct-utilization, such as for space heating, swimming pools and balneology. The Dezhou geothermal reservoir is situated within the Dezhou depression. It is bounded by the Bianlinzhen Fault on the east, the Cangdong Fault on the

west, the Xiaoyuzhuang Fault on the south, and the Xisongmen Fault on the north. All of these faults appear to act as permeable boundaries, which are presented in Figure 2. Some other faults, such as the Jianhe fault, intersect the Dezhou reservoir, and then result in anisotropic permeabilities of the reservoir.

According to stratigraphic data from boreholes (Figure 3) and interpretation of geophysical explorations, the Cenozoic sedimentary strata appear to be more than 3100 m thick.

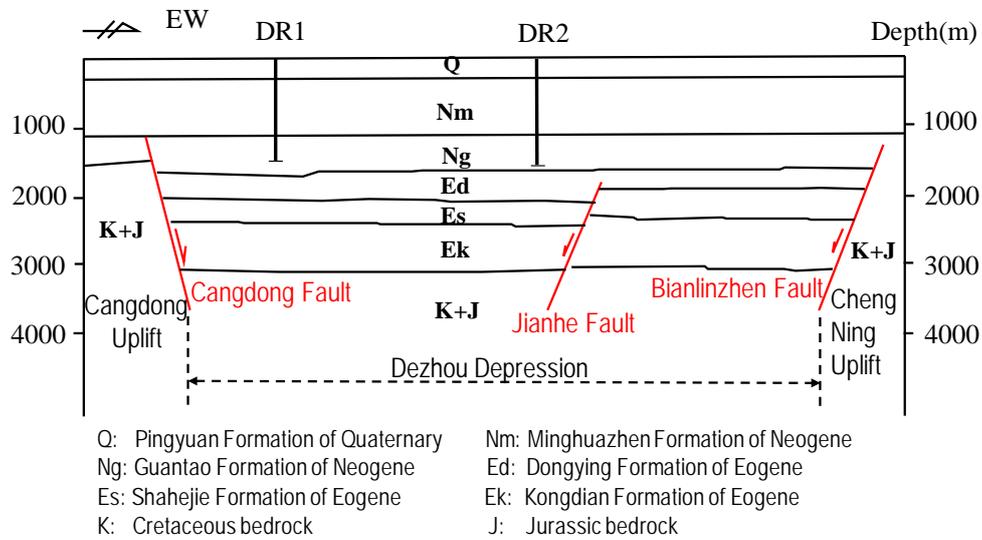


Figure 2: Tectonic cross-section of the Dezhou Depression

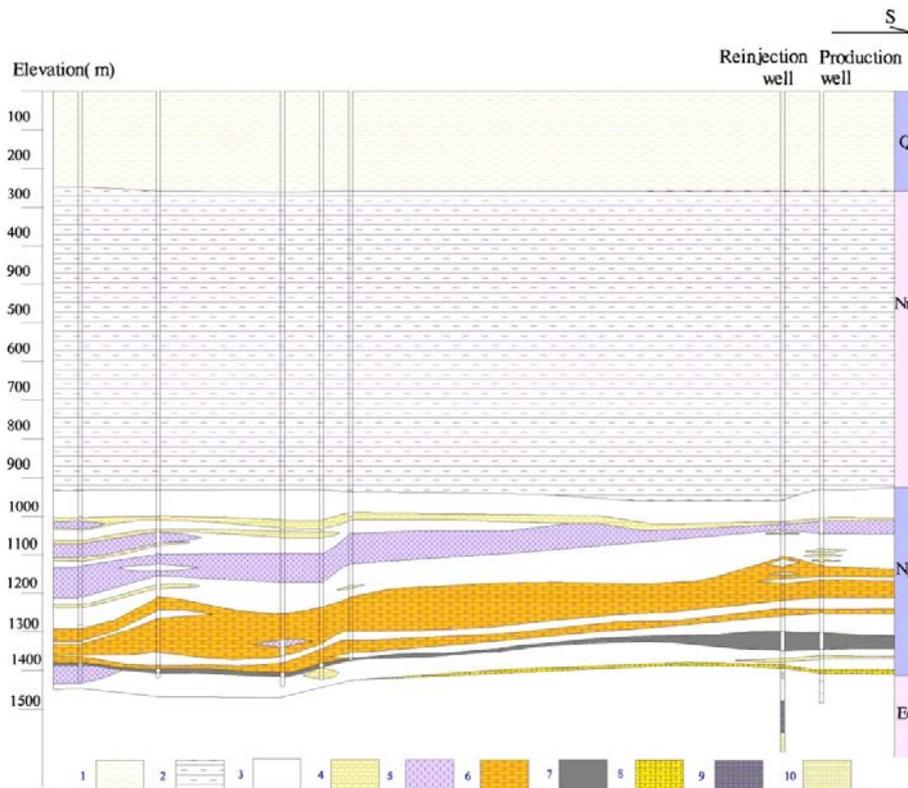


Figure 3: Borehole cross-section in the Dezhou Geothermal Field
 Q-Pingyuan Formation of Quaternary: 1-clay and sandy clay;
 Nm-Minghuazhen Formation of Neogene: 2-upper section: mudstone, silt and fine sand, low diagenesis, lower section: argillite, silt and fine sand, high diagenesis;
 Ng-Guantao Formation of Neogene: 3-argillite, 4-fine sandstone, 5-medium sandstone, 6-coarse sandstone, 7-intrusive rock, 8-conglomerate;
 Ed-Dongying Formation of Eocene: 9-sandy argillite, 10-argillaceous sandstone

The distribution of groundwater water age reveals aspects of the flow regime (Bethke and Johnson 2008) and groundwater renewability (Chen *et al.* 2003, 2004). A geothermal water age contour map is compiled (shown in Figure 4) using the corrected radiocarbon ages. The results suggest that the geothermal water ages in the study area range from 11,000 to 25,000 years. It is believed that geothermal water more than 10,000 years old does not interact with the modern water cycle, and therefore the Dezhou geothermal reservoir is non-renewable. In other word, it belongs to a closed geothermal system without modern recharge.

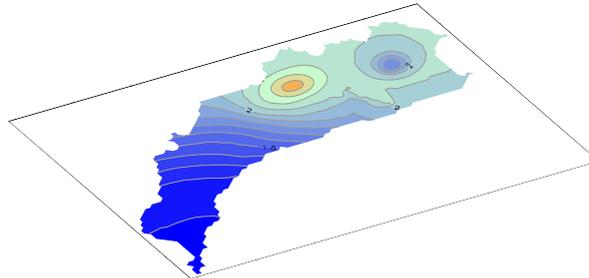


Figure 4 Geothermal water age contours in the Dezhou Geothermal Reservoir

3. Development Of Geothermal Water

There are 302 production wells in Dezhou geothermal reservoir, with the total production rates of 38.1 million m³ annually. 80 are located in the urban area of Dezhou City and 15 are located in the urban area of Pingyuan County.

Attributed to heavy development and very limited recharge, fast water level drawdown occurred in the sandstone aquifers of Neogene Guantao Formation (Figure 5). The water level in the urban area of Dezhou has dropped from 8.3 m artesian height in 1997 to 93 m below ground surface in Mar. 2017, with an annual decrease of 8.2 from Mar. 2013 to Mar. 2017. Meanwhile, the annual production per unit water level drawdown presents exponential order attenuation as follows (Table 1, Figure 6):

$$y = 303.9e^{-0.052x} \quad (R^2 = 0.9265) \quad (1)$$

Where: y-annual production per unit water level drawdown, x-water level depth.

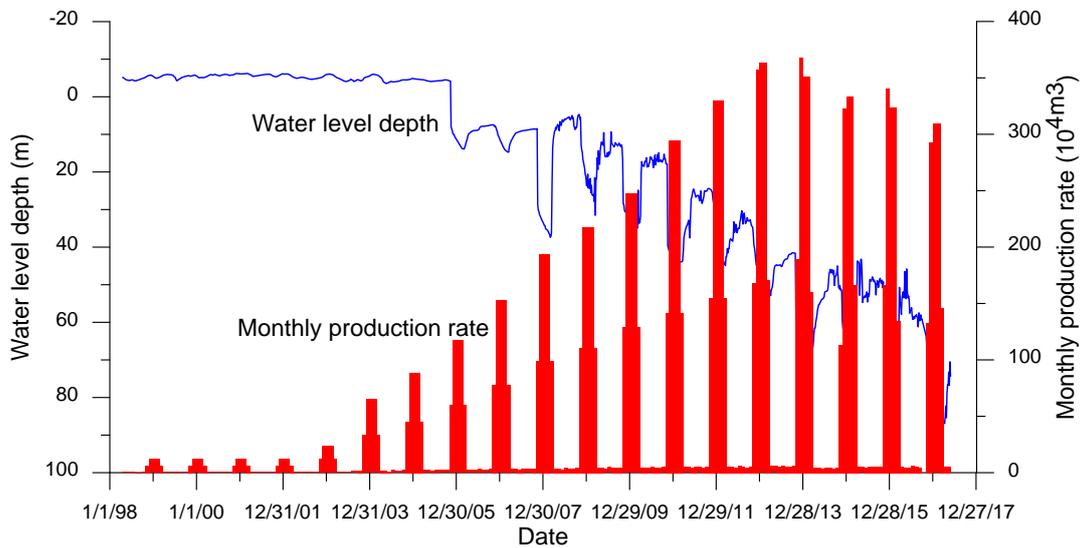


Figure 5: Production and water level response history of Well DR1 in the sandstone aquifer of Neogene Guantao Formation in Urban Dezhou, Northern China

Table 1 Annual production per unit drawdown variations response to water level changes of the sandstone aquifers of Neogene Guantao Formation in Urban Dezhou, Northern China

Year	Production (10 ⁴ m ³)	Average water level during space heating(m)	Water level drawdown(m)	Annual production per unit drawdown (10 ⁴ m ³ /m)
2007	699.86	10.6	10.6	66.02
2008	843.46	16.37	5.77	51.52
2009	951.64	16.53	0.16	57.57
2010	1095.57	23.81	7.28	46.01
2011	1252.22	33.29	9.48	37.62
2012	1380.21	34.95	1.66	39.49
2013	1497.32	45.81	10.86	32.69
2014	1863.58	55.72	9.91	33.45
2015	2052.38	55.83	0.11	36.76
2016	2134.22	59.57	3.74	35.83
2017	2200	84.5	24.93	26.04

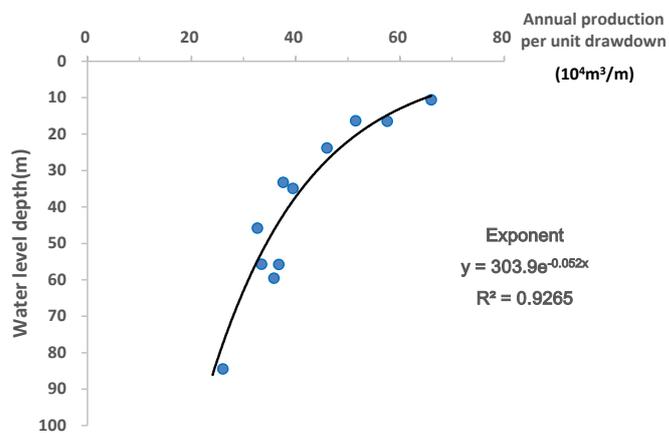


Figure 6: Annual production per unit water level drawdown variations response to water level changes of the sandstone aquifers of Neogene Guantao Formation in Urban Dezhou, Northern China

The geothermal aquifer is overlain by a colder groundwater aquifer in Minghuazhen Formation, at a depth of 190-250 m. It is the main water-supply source in the Dezhou City, and has been pumped since 1965. Due to arbitrary increase of groundwater exploitation--up to 69,900 m³/day, the groundwater level is continuously falling. In response to extended heavy pumping, the groundwater level has fallen from 2 m to 140 m below ground surface and a depression cone with an area of about 3,200 km² has formed. At present, the groundwater level is still decreasing at a rate of 3-4 m/year. Accompanying this significant lowering of groundwater level (Figure 7), land subsidence at a rate of 15-60 mm/year has occurred. The affected area basically coincides to the depression cone. The cause of the subsidence is considered to be compaction of high-porosity, low-permeability mudstone at 90-150 m depth.

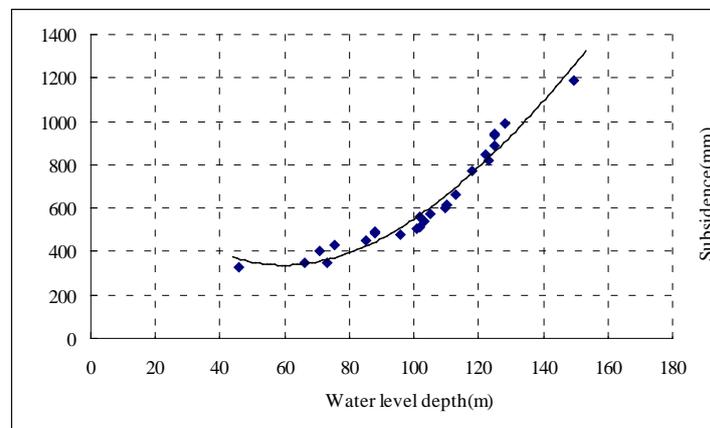


Figure 7: Relation between water level depth and subsidence in Urban Dezhou

4. Methodology

For the purpose of sustainable development of geothermal resources, especially for the sandstone aquifers with very little geothermal water recharge in China, reinjection has become an effective means for sustainable and environmentally friendly geothermal utilization. It is efficient for geothermal water after space heating disposal, as well as to provide additional recharge to geothermal aquifers. Therefore, reinjection counteracts fast pressure (water level) drawdown induced by heavy development, and extracts more thermal energy from reservoir rocks (Axelsson, 2008), together with enlarges production capacity. Meanwhile, reinjection can also mitigate land subsidence and be used to maintain geothermal manifestations (artesian wells, natural hot springs). But due to scaling, clogging and corrosion, the reinjection rates decrease dramatically in sandstone aquifers.

Some operational dangers and problems are associated with reinjection. These include the possible cooling of production wells, often because of short-circuiting and cold-front breakthrough (Axelsson, 2008). Also scaling and clogging of surface equipment and injection wells can occur because of the precipitation of chemicals in the water which leads to decreased reinjection rates in sandstone aquifers. Injection into sandstone reservoirs has, furthermore, turned out to be problematic.

In China, the earliest geothermal reinjection experiments were successfully implemented in the urban area of Beijing in 1974 and 1975 from a dolomite aquifer. At the end of the 1980's, reinjection tests were carried out in the Tertiary sandstone reservoir in Tianjin. At the beginning of the tests, about 30-50 m³/h was reinjected into the reservoir but injectivity decreased quickly (Liu, 2008; Wang, 2008). Because of this, extensive testing and research are prerequisites to successful reinjection operations.

A reinjection experiment for a sandstone aquifer of the Neogene Guantao Formation, which is

widely distributed in North China Plain, was successfully conducted in Pingyuan County, Dezhou City, Shandong Province, China.

4.1 Large diameter bore hole drilling and grave packing for the reinjection well

4.1.1 Large diameter Reaming

In order to enlarge the flow surface area and transmissibility capacity of the reinjection well, multilevel reaming has been conducted to augment bore hole diameter (Figure 8):

The first bore hole diameter: 250 mm, drilled to 1600 m;

The second bore hole diameter: 350 mm, drilled to 1450 m;

The third bore hole diameter: 445 mm, drilled to 1400 m;

The fourth bore hole diameter: 550 mm, drilled to 220 m.

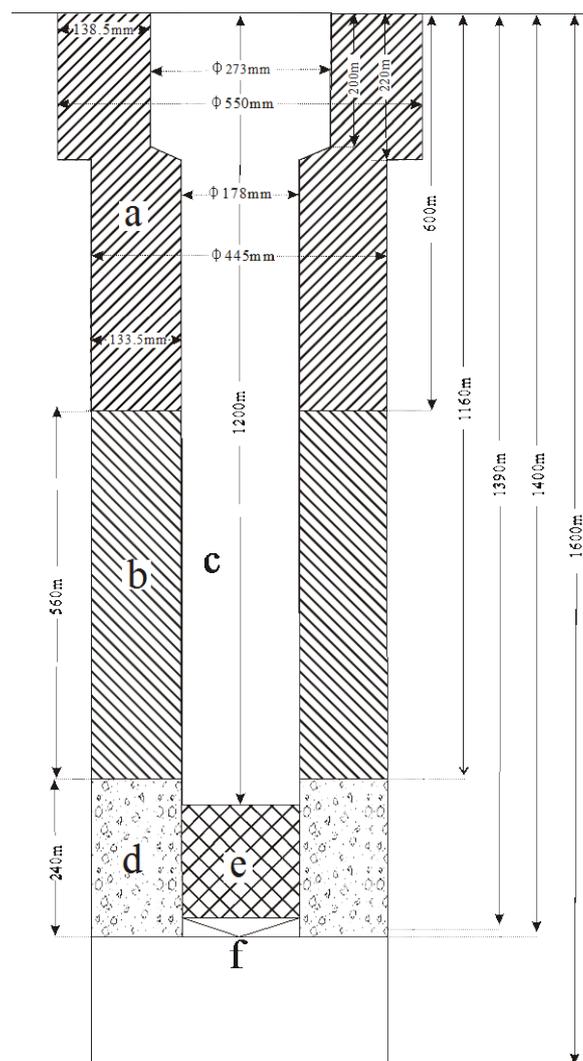


Figure 8: Configuration of reinjection well (a-sandy clay, b-clay, c-well tube, d-gravel pack, e-wire-wrapped screen, f-sump)

4.1.2 Gravel packing

Before gravel packing, back flushing should be carried out to wash the mud cake along the internal face of the reinjection bore hole. This is the effective measure to dredge the geothermal water

bearing channel around the bore hole. On the same time, the mud fluid viscosity also has to be displaced to 16~18 second. Totally, 2~3 days are needed for back flushing and mud fluid viscosity displacement. If the mud fluid viscosity is too large, it is difficult to pack gravel, and easy to pack gravel at dislocation; and then make the gravels to cement. Hence, the permeability along the inner face of the bore hole will be decreased dramatically.

After back flushing and mud fluid displacement, a gravel pack was installed for the depth ranging from 1128.1 m to 1400.75 m at a rate of 3~6 m³/h. From 1108.1 m to 1128.1 m, clay was used as waterproof material.

4.1.3 Completion

Stainless steel wire-wrapped screen pipe completion is adopted for the reinjection well, with the screen porosity of 13%. The main aquifers are located in Neogene Guantao Formation. Screened intervals are at depths of 1128.10~1161.72, 1173.44~1218.55, 1241.11~1264.38, 1320.99~1332.17, 1366.85~1389.20 m, with the cumulative screened length of 135.53 m. The specification of the screen pipe is: $\phi 177.8 \times 8.05$ mm, and the steel mesh spacing between is 0.75 mm.

4.2 Pumping test

A pumping test was conducted for 8850 minutes from Sep. 27 to Oct. 3, 2012, with the reinjection well as pumping well, and the production well as observation well. The static water level depth in the pumping well is 30.69m and 31.81m in the observation well. The steady pumping rate was 84.25 m³/h (Figure 8). The drawdown ranged from 4.27 to 7.74m in the pumping well and from 0.005 to 1.01m in the observation well (Figure 9).

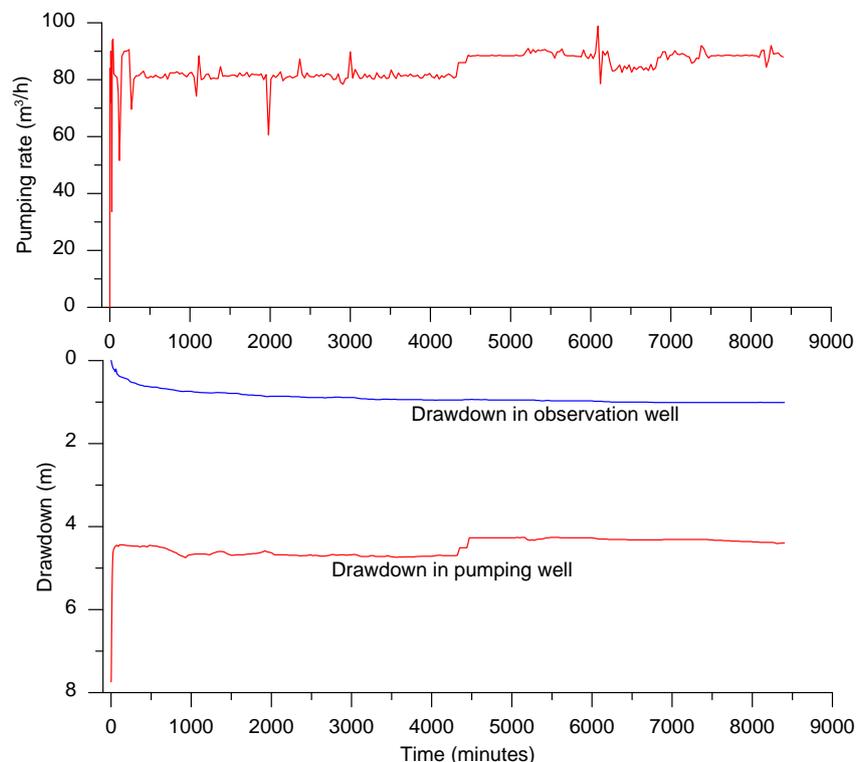


Figure 9: Pumping rates variations along with drawdowns in pumping and observation wells

Some hydrogeological parameters are calculated by using curve fitting of Theis model (Figure 10). They are: Transmissivity, 972 m²/d; hydraulic conductivity, 6.75 m/d (the average of aquifer thickness is 144m); elastic storativity, 3.19×10^{-4} .

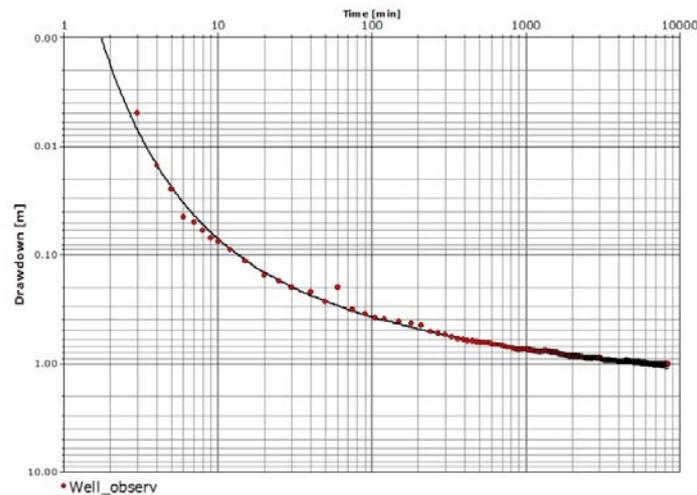


Figure 10: Parameters calculating by using Theis Curve Fitting based on Observation well data

4.3 Geothermal tail water treatment

Aiming to raise the reinjection rate and ensure the long term effective operation, it is essential to treat the geothermal tail water for reinjection as indicated in the following steps:

1. The first step is coarse filtering, for the purpose of filtering suspended solids and chemical precipitations to increase the reinjection efficiency.
2. The second is fine filtering with the precision of 3~5 μm to filter suspended solids and chemical precipitations together with microorganism filtering.
3. The third step is gas escaping to avoid gas blocking.
4. The last and the most important step is back flushing. When the pressure difference between the two sides of filtering equipment reaches 50~60 kPa, back flushing must be implemented at a rate of 12~15 L/s m^2 .

4.4 Re-pumping

It is necessary to re-pump from the reinjection well for 7 days until the re-pumped water is to be clear and no sand (Figure 11). For instance, when the rate of re-pumped water is 80 m^3/h , the re-pumped time should be 4 hours.



Figure 11: Re-pumping during the reinjection until the re-pumped water to be clear and without sand (Left-at the beginning of re-pumping; Right-at the end of re-pumping)

4.5 Tracer test

A tracer test was conducted with the third reinjection experiment from Jan. 20th to Mar. 16th 2015. The geothermal water temperature in the production well was 53°C and reinjected tail water was 32.8°C. The tracer chosen was ammonium molybdate, 50 kg of which was injected into the reinjection well. Comparing the Mo⁶⁺ concentration in water samples taken before and at the start of the test and considering the analysis error, the background threshold of Mo⁶⁺ is estimated to be 0.014 µg/ml. Figure 12 shows the Mo⁶⁺ concentration changes in the geothermal waters from the production well. The peak of the tracer concentration occurred about 31.25 days (750 hours) after injection and the tracer recovery lasted 42.5 days (1020 hours). After this time, the tracer is considered to re-enter the production well through recirculation between production and reinjection wells.

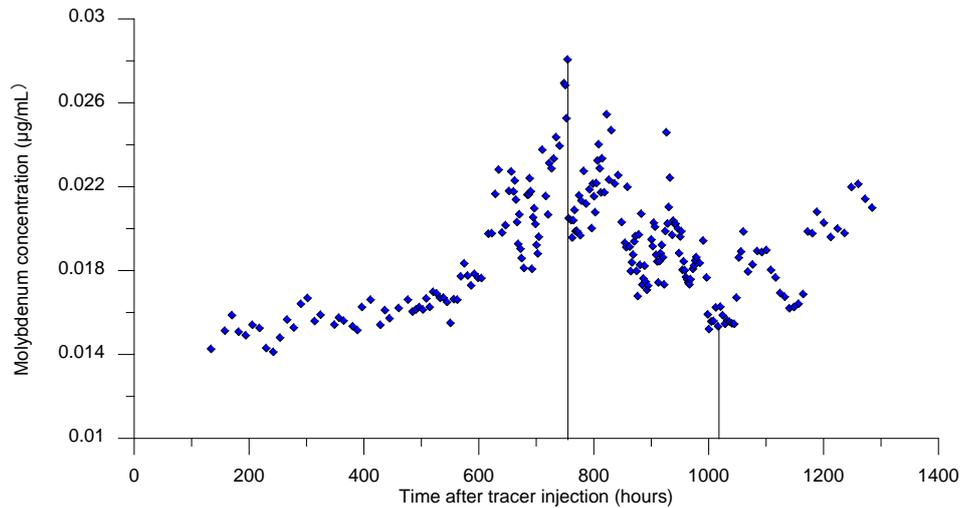


Figure 12 Breakthrough curve for tracer test from Jan. 20th to Mar. 16th, 2015

5. Reinjection, Tracer Test Results and Analysis

The distance between the production and reinjection wells is 232 m (Figure 3), with a static water level depth in the reinjection well of 30.69 m and 31.81 m in the production well. The depth to the sandstone aquifer of Neogene Guantao Formation is 1130.70~1393.30 m with the geothermal water temperatures ranging from 50 to 52 °C and a TDS of 5221.8 mg/l. As shown in Figure 13, the experiment continued for 63 days, from Oct. 13 to Dec. 15, 2012, with the biggest reinjection rate of 70 m³/h accompanying the highest water level increase in reinjection well of 28.65 m and the highest water level increase in the production well of 3.55 m.

5.1 Correlation between reinjection rates and water level increases

The reinjection fluids were not injected under pressure. From table 2 and Figure 13, it can be seen that the reinjection rates are in proportion to the water level increases with the equation of polynomial correlation as follows:

$$y = 2.9864 - 0.1283x + 0.0289x^2 - 0.0006x^3 + 0.000004x^4 \quad (R^2 = 0.9997) \quad (2)$$

Where: y-reinjection rates, x-water level increase.

Simultaneously, it is obviously shown in Table 2 and Figure 15 that the reinjection rates per unit water level increase has no decrease trend with the increase of reinjection rates. Therefore, there is still a potential to increase the reinjection rates corresponding to the water level increase.

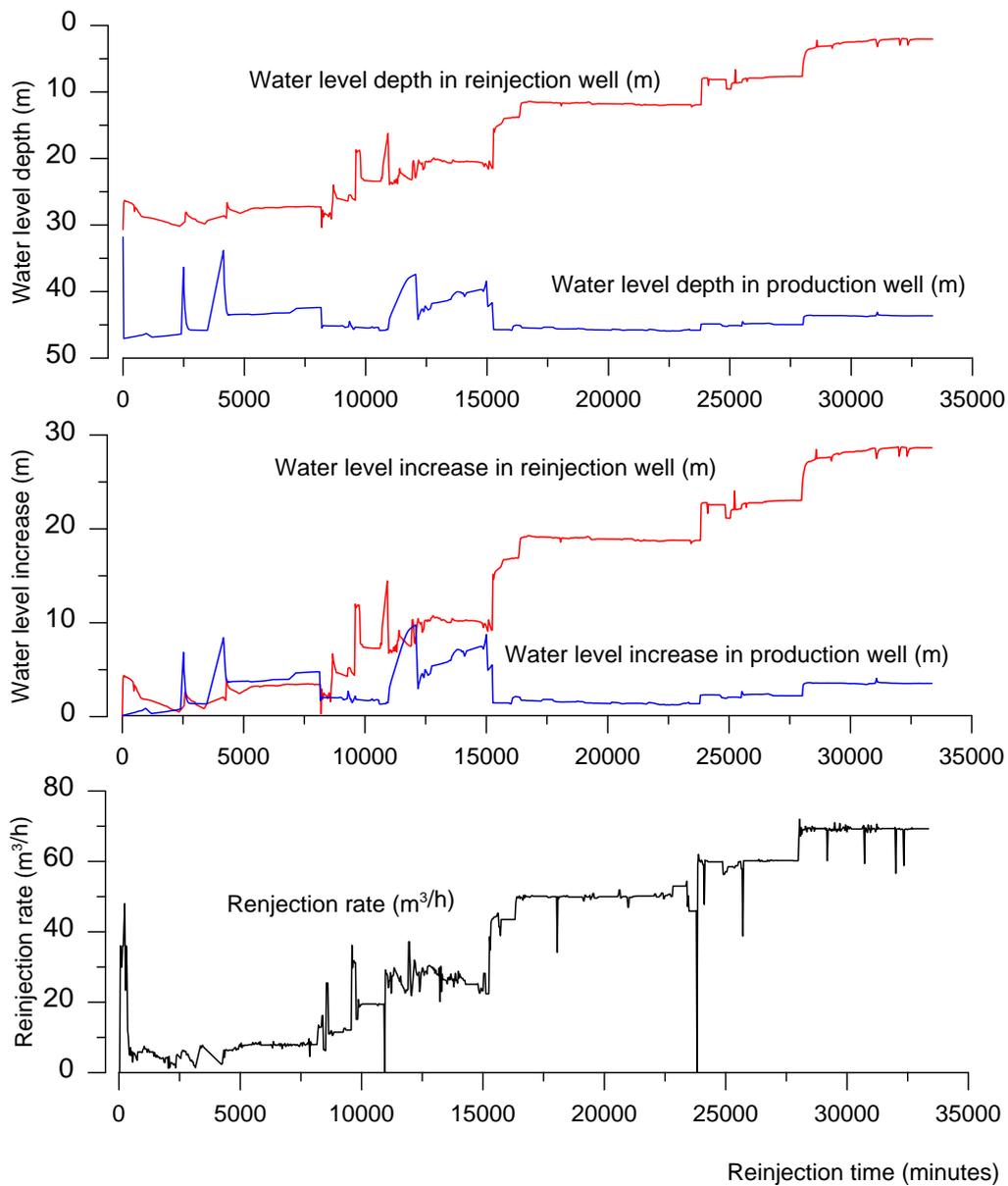


Figure 13: Reinjection rates vs water level increases in production and reinjection wells over the period of Oct. 13~Dec. 15, 2012

Table 2 Reinjection rates vs water level increases

Reinjection rate (m ³ /h) ①	Water level increase (m) ②	Reinjection rate per unit water level increase (=①/②)(m ³ /h·m)
7.8	3.49	2.23
11.5	4.49	2.56
19.5	7.27	2.68
25.1	10.22	2.46
43.51	16.82	2.59
50	19.04	2.63
60.26	23	2.62
69.3	28.66	2.42

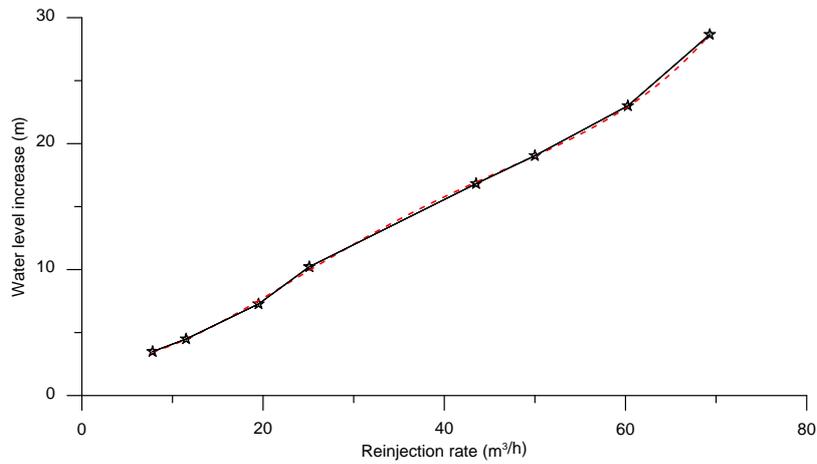


Figure 14: Relationship of reinjection rates vs water level increases (Black solid line: measured data, red dash line: fitted trend)

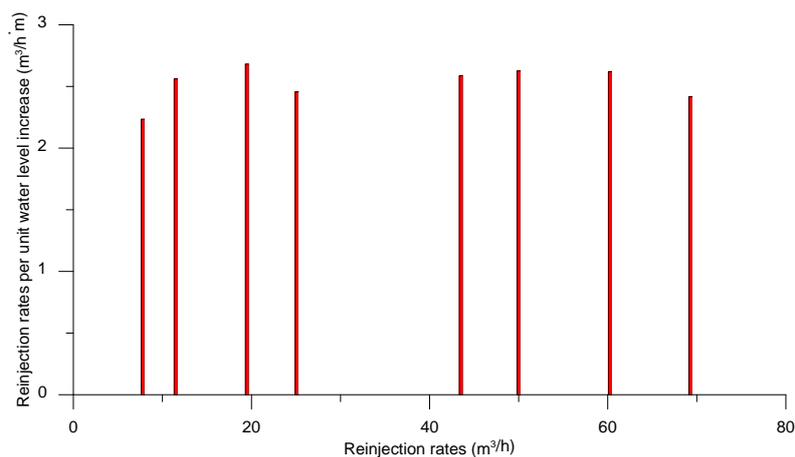


Figure 15: Correlation between Reinjection rates per unit water level increase and reinjection rates

5.2 Correlation of water temperatures between reinjection and production wells

At the experiment from Oct. 13 to Dec. 15, 2012, the temperatures of reinjection water are similar to that of production well, ranging from 50 to 52 °C; therefore, the influence of reinjection water on the production water cannot be found. Cooling of production well or cold-front breakthrough cannot be determined. For the purpose of solving this issue, and also testing the long term effectivity of reinjection, the second reinjection experiment was implemented in the entire space heating period from Nov. 14, 2013 to Mar. 14, 2014 and a third one with a tracer test from Jan. 20th –Mar. 16th 2015. As illustrated in Figures 15-16, the reinjection water, with the temperatures varying from 30 to 32 °C, had no influence on water temperatures of 53 °C in the production well for an entire space heating period of 120 days.

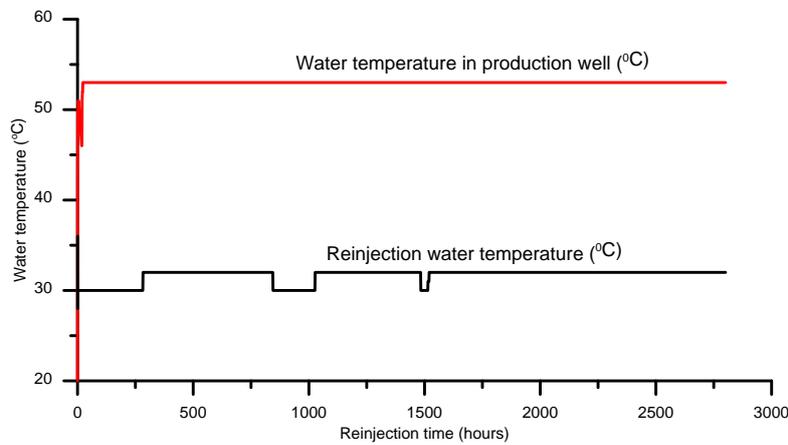


Figure 15: Contrast of reinjection water temperatures to those in production well over the period from Nov. 14, 2013 to Mar. 14, 2014

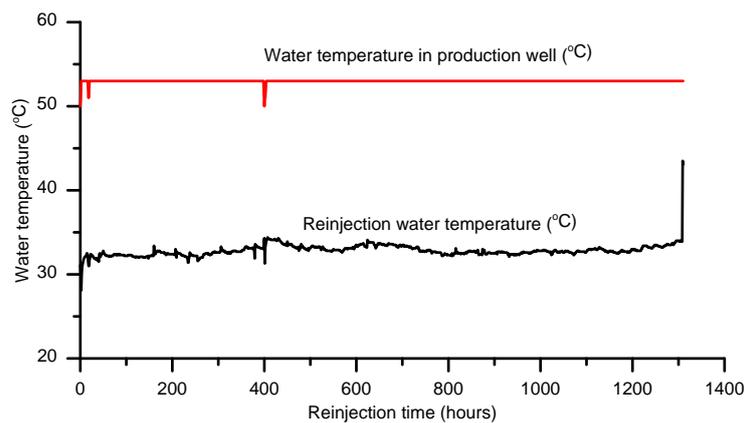


Figure 16: Contrast of reinjection water temperatures to those in production well over the period from Jan. 20th to Mar. 16th 2015

5.3 Hydrogeological parameters calculation based on tracer test

The hydraulic conductivity around production and reinjection wells is calculated as follows:

$$u = L/t \quad (3)$$

$$v = n_e u = KI \quad (4)$$

$$I = \Delta H / L \quad (5)$$

$$T = KM \quad (6)$$

Where: u - actual geothermal water velocity, L - distance between production and reinjection wells, t - lasted time of tracer transported from production to reinjection wells, v - permeable velocity, n_e - effective porosity, I - hydraulic gradient, K - hydraulic conductivity, and T - transmissivity.

There is temperature difference between the production and reinjection well, which causes different height of water column at the same downhole pressure. Therefore, it's necessary to adjust the water column in the reinjection well according to formula (7).

$$\rho_1 g(H - h_1) = \rho_2 g(H - h_2) \quad (7)$$

$$\text{Thus, } h_2 = H - \frac{\rho_1(H-h_1)}{\rho_2} \quad (8)$$

The actual water head difference can be calculated by formula (9).

$$\Delta H = h_0 - h_2 \quad (9)$$

Where,

H - height from surface to the bottom of the reinjection well (m), here $H=1402.75$ m;

ΔH - static water level difference between reinjection well and production well with stable reinjection rate (m);

h_0 - static water level of production well with stable reinjection rate (m), here $h_0 =62.25$ m;

h_1 - static water level of reinjection well with stable reinjection rate (m), here $h_1=39$ m;

h_2 - corrected static water level of reinjection well with stable reinjection rate (m);

ρ_1 - density of 32°C reinjection water (kg/m³), here $\rho_1=994.6$ kg/m³;

ρ_2 - density of 53°C production water (kg/m³), here $\rho_2=986.4$ kg/m³.

According to formula (3) to (8), it can be calculated out that $h_2=27.66$ m, $I=0.15$ and $K_2=16.81$ m/d (when the fluid is 53°C). Formula (10) below is used to calculate the hydraulic conductivity of 32°C reinjection fluid.

$$k = \frac{K\mu}{\rho g} \quad (10)$$

Where,

k - intrinsic permeability of the reservoir (m²);

K - hydraulic conductivity of the fluid (m/s);

μ - dynamic viscosity of the fluid kg/(m·s) or N·s/m²;

ρ - density of the fluid (kg/m³),

g - acceleration of gravity (m/s²).

Here the intrinsic permeability k does not change, so there is:

$$K_1 = \frac{K_2\mu_2\rho_1}{\rho_2\mu_1} \quad (11)$$

Where,

K_1 - hydraulic conductivity of 32°C reinjection fluid (m/s);

K_2 - hydraulic conductivity of 53°C production fluid (m/s), here it's 16.81 m/d;

μ_1 - dynamic viscosity of 32°C production fluid kg/(m·s) or N·s/m², here is 7.64×10^{-4} kg/(m·s);

μ_2 - dynamic viscosity of 53°C production fluid kg/(m·s) or N·s/m², here is 5.19×10^{-4} kg/(m·s);

ρ_1 - density of 32°C reinjection water (kg/m³), here $\rho_1=994.6$ kg/m³;

ρ_2 - density of 53°C production water (kg/m³), here $\rho_2=986.4$ kg/m³.

g- acceleration of gravity (m/s^2).

It can be calculated out that when the fluid is 53°C , $K_1=11.51$ m/d.

The reinjected fluid goes down to the reservoir, mixes with the geothermal fluid and the temperature increases as it flows. The calculated actual hydraulic conductivity, for which use the time when the tracer arrived, is 11.51 to 16.81 m/d. Using the time when maximum tracer concentration arrived (31.25 day) to calculate, the actual hydraulic conductivity is 10.14 to 14.81 m/d. Since the average thickness of the aquifer is about 144 m, the transmissivity is 1.46×10^3 to $2.13 \times 10^3 \text{m}^2/\text{d}$. The K and T can be up to 2.2 times in contrast to the parameters calculated by pumping test.

6. Conclusions

(1) Reinjection of geothermal tail water into porous sandstone aquifers is technically feasible, with the prerequisite of careful study on geological and hydrogeological settings, as well as the hydrogeological parameters of the aquifer.

(2) Overcoming rapid clogging of aquifers next to reinjection wells in the porous sandstone aquifer by fine sand and precipitation material, the following measures have to be adopted: large diameter reaming and gravel packing to enlarge the flow surface area and increase the permeability around the reinjection well; coarse filtering, fine filtering with the precision of 3~5 μm ; gas escaping, back flushing when the pressure difference between the two sides of filtering equipment reaches 50~60 kPa; re-pumping for the reinjection well at an interval of reinjection for 7 days.

(3) The distance of 232 m between reinjection and production wells is suitable for porous sandstone aquifers of Neogene Guantao Formation in North China Plain; this can alleviate the rapid water level declines and does not induce water cooling in production wells for an entire space heating period of 120 days in North China.

(4) The hydraulic conductivity and transmissivity calculated by tracer test are 2.2 times of that calculated by pumping test.

(5) Sustainable development of non renewable sandstone aquifers can be achieved based on reinjection.

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