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Reinjection Experiment for a Sandstone Aquifer in Pingyuan, China

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ABSTRACT

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 waste water disposal, as well as to provide additional recharge to geothermal aquifers. Therefore, reinjection counteracts fast pressure drawdown induced by heavy development, and extracts more thermal energy from the reservoir rocks, together with a larger 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 can decrease dramatically in sandstone aquifers.

A reinjection experiment in sandstone aquifers of the Neogene Guantao Formation, which are widely distributed in North China Plain, has 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 aquifer is 1130.70 -1393.30 m, and the TDS of geothermal water is 5221.8 mg/l. The experiment has continued for 54 days, with the largest reinjection rate of 70 m^3/h, accompanying the water level increase in the reinjection well of 28.65 m, and the water level increase in production well of 3.55 m. This paper describes the geological and geochemical 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, as well as filtering and re-pumping the reinjection well at an interval of reinjection for 7 days.

1. INTRODUCTION

Due to heavy development and very limited recharge, rapid pressure drawdown occurred in most of the sandstone 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.

It is essential to implement reinjection to counteract rapid pressure drawdown induced by heavy development and extract more thermal energy from reservoir rocks. Other possible benefits of reinjection are increasing production capacity and providing a solution to the problem posed by the disposal of waste geothermal fluid that 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.

For the purpose of increasing the reinjection rate for sandstone aquifers, a reinjection experiment has been conducted in Pingyuan County, Dezhou City, Shandong Province, China, from Oct. 13, 2012 to Dec. 15, 2012.

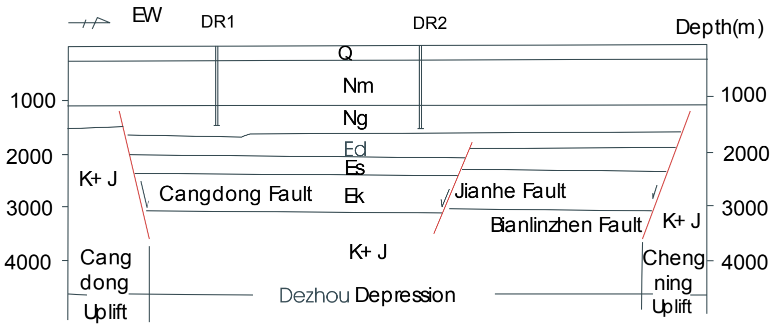
2. GEOLOGIC AND HYDROGEOLOGICAL SETTING

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, as shown in Figure 2. Some other faults, such as the Jianhe fault, intersect the Dezhou reservoir, and 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.



Q: Pingyuan Formation of Quaternary
Nm: Minghuazhen Formation of Neogene
Ng: Guantao Formation of Neogene
Ed: Dongying Formation of Eogene
Es: Shahejie Formation of Eogene
Ek: Kongdian Formation of Eogene
K: Cretaceous bedrock
J: Jurassic bedrock

Figure 2: Tectonic cross-section of the Dezhou Depression

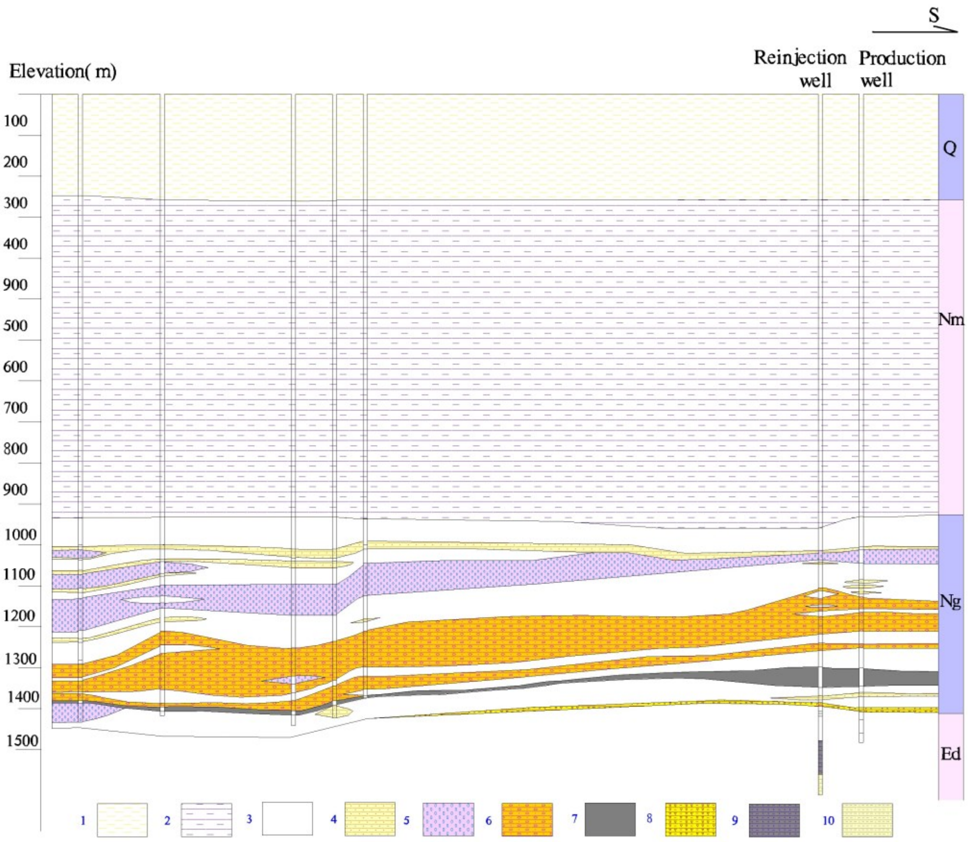


Figure 3: Borehole cross-section in the Dezhou Geothermal Field

(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 Eogene: 9-sandy argillite, 10-argillaceous sandstone)

3. DEVELOPMENT OF GEOTHERMAL WATER

There are 254 production wells in Dezhou geothermal reservoir, with the total production rates of 38.1 million m^3 annually. 80 are located in the urban area of Dezhou City, and 15 are located in the urban area of Pingyuan County.

Rapid drawdown attributed to the heavy development and very limited recharge occurred in the sandstone aquifers of Guantao Formation of Neogene (Figure 4, 5). The water level in the urban area of Dezhou changed from 8.3 m artesian height in 1997 to 60 m below ground surface in 2013, with an average annual decrease of 3.4 m.

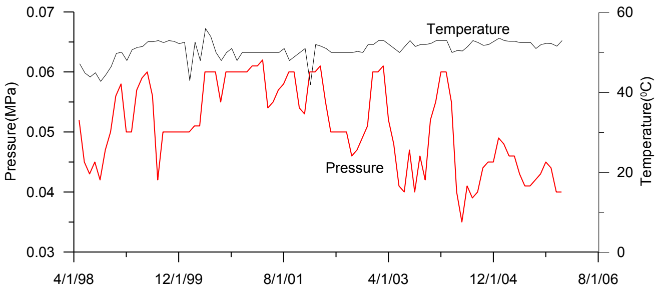


Figure 4: Pressure variations vs water temperatures for well DR1 in Urban Dezhou

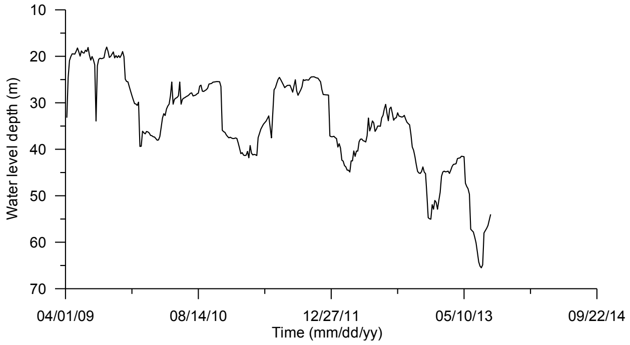


Figure 5: Pressure variations for well Zhongmao in Urban Dezhou

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 its current value of 69,900 m^3/day , the groundwater level is continuously falling. In response to extended heavy pumping, the deepest depth to the groundwater level has fallen from 2 m to 140 m, and a depression cone with an area of about 3,200 km^2 has formed. At present, the groundwater level is still decreasing at a rate of 3-4 m/year. Additionally, land subsidence has occurred at a rate of 15-60 mm/year (Figure 6). The affected area coincides with the depression cone. The cause of the subsidence is considered to be compaction of high-porosity, low-permeability mudstone at 90-150 m depth.

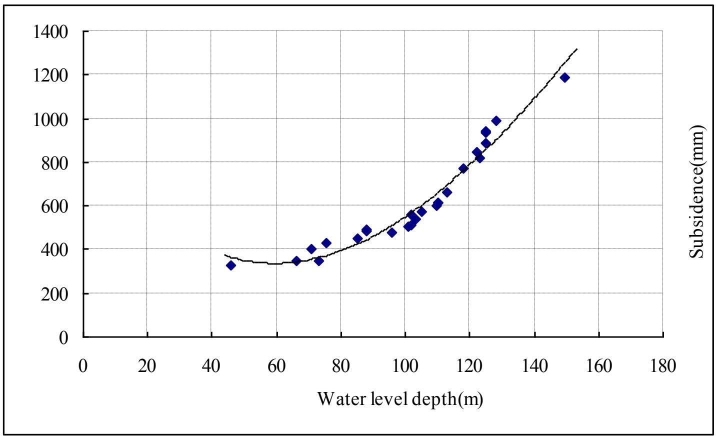


Figure 6: Relation between water level depth and subsidence in Urban Dezhou

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 waste water disposal, as well as to provide additional recharge to geothermal aquifers. Therefore, reinjection counteracts fast pressure drawdown induced by heavy development, and can lead to the recovery of more thermal energy from reservoir rocks (Axelsson, 2008) and increased production capacity. Meanwhile, reinjection can also mitigate land subsidence and be used to maintain geothermal manifestations (artesian wells, natural hot springs). There are some operational dangers and problems associated with reinjection, including the possible cooling of production wells due to short-circuiting and thermal breakthrough (Axelsson, 2008) and scaling and clogging in surface equipment and injection wells due to the precipitation of chemicals in the water which leads to the reinjection rate decreasing dramatically in sandstone aquifers. Injection into sandstone reservoirs has, furthermore, turned out to be problematic. In China, the earliest geothermal reinjection experiments had been successfully implemented in the urban area of Beijing in 1974 and 1975 in 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 m^3/h of waste water was injected into the reservoir. However, the injectivity decreased quickly (Liu, 2008; Wang, 2008). Because of this, extensive testing and research are prerequisites to successful reinjection operations.

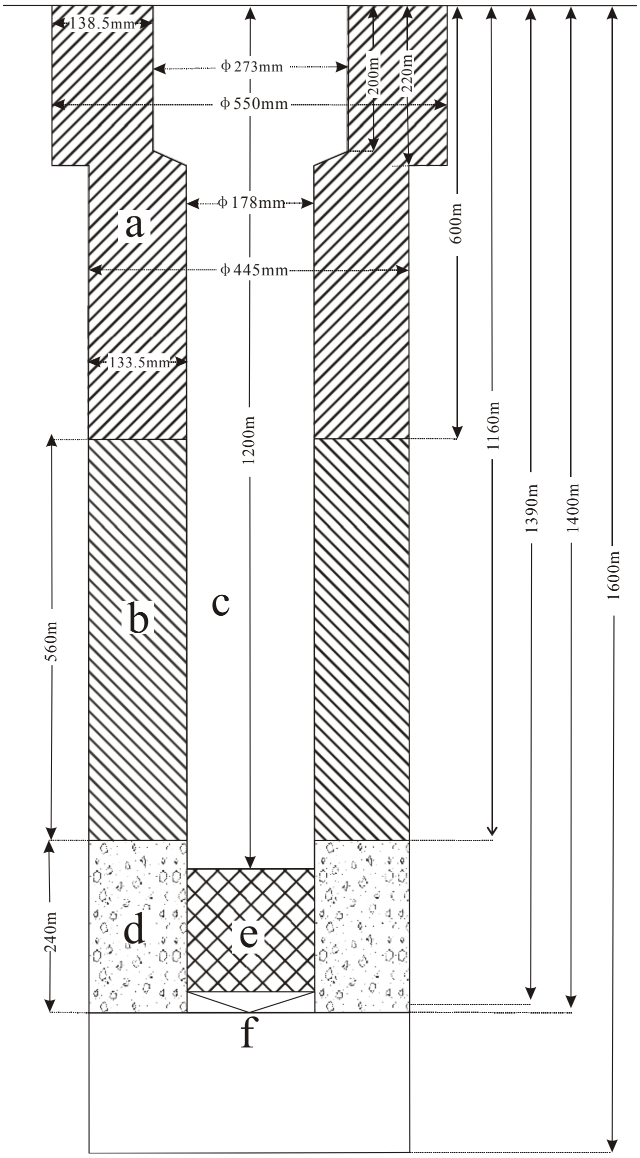


Figure 7: Configuration of reinjection well (a-sandy clay, b-clay, c-well tube, d-gravel pack, f-precipitation tube)

A reinjection experiment for sandstone aquifers of Neogene Guantao Formation, which are widely distributed in North China Plain, has been 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 7):
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 forth bore hole diameter: 550 mm, drilled to 220 m.

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 bore hole. This is the effective measure to dredge the water bearing channel. At the same time, the mud viscosity must also be displaced to 16-18. In total, 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, gravel packing was implemented for the depth ranging from 1128.1 m to 1400.75 m, with the velocity of 3~6 m^3/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 Guantao Formation of Neogeno, and the screen pipes are in the depth 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 length of 135.53 m. The specification of the screen pipe is：φ177.8×8.05 mm, and the steel mash 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 a pumping well, and the production well as an 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 is 84.25 m^3/h (Figure 8), and the drawdown ranges from 4.27 to 7.74m in the pumping well, and from 0.005 to 1.01m in the observation well (Figure 8).

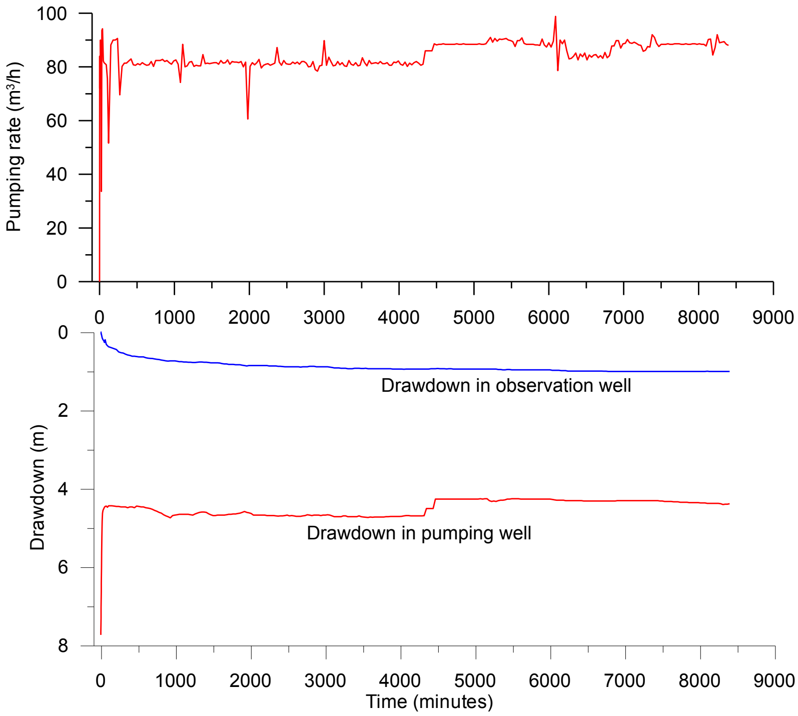


Figure 8: Pumping rates variations along with drawdowns in pumping and observation wells

Some hydrogeological parameters are calculated by using curve fitting of Theis model (Figure 9): Transmissivity: 972 m^2/d, hydraulic conductivity: 6.39 m/d, elastic storativity: 3.19×10^{-4}.

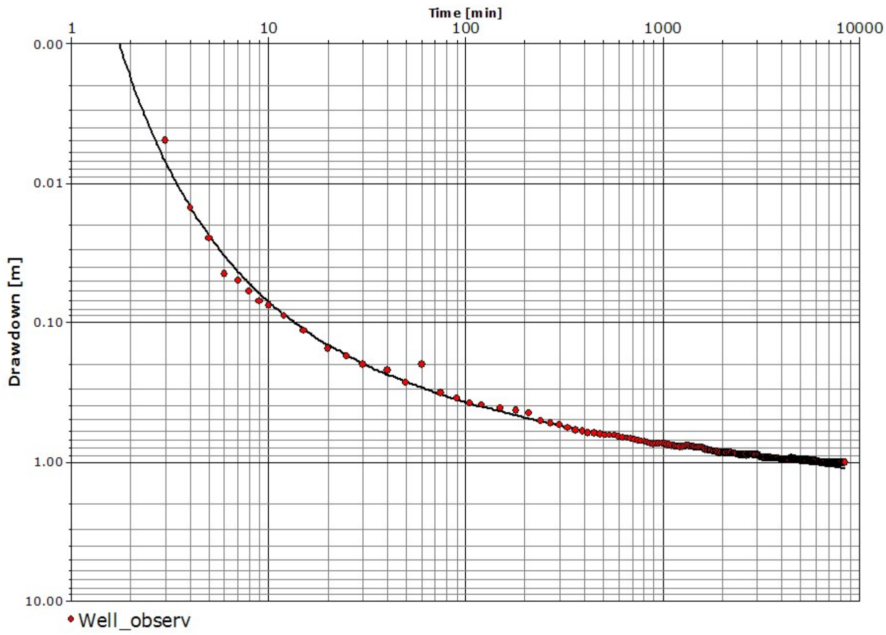


Figure 9: Parameters calculating by using Theis Curve Fitting based on Observation well data

4.3 Geothermal waste water treatment

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

The first step is coarse filtering, for the purpose of suspended solids and chemical precipitations filtering, so as to increase the reinjection efficiency.

The second is fine filtering with the precision of 3-5 μm for fine suspended solids and chemical precipitations filtering, together with microorganism filtering.
The third is gas venting, to avoid gas blocking.
The last and the most important is back flushing. When the pressure difference between the two sides of filtering equipment reaches 50-60 kPa, back flushing must be implemented, with the intensity of 12-15 L/s • m^2.

4.4 Re-pumping

It is necessary to re-pump the reinjection well at an interval of reinjection for 7 days, until the re-pumped water is clear and contains no sand (Figure 10). For instance, when the rate of re-pumped water is 80 m^3/h, the re-pumping time should be 4 hours.

Figure 10: 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)

5. REINJECTION RESULTS AND ANALYSIS

The distance between the production and reinjection wells is 232 m (Figure 3), with the static water level depth in reinjection well of 30.69 m, and 31.81 m in production well. The depth to sandstone aquifer of Neogene Guantao Formation is 1130.70-1393.30 m, with the geothermal water temperatures ranging from 50 to 52 ^{0}C and the TDS of 5221.8 mg/l. As shown in Figure 11, the experiment has continued for 63 days, from Oct. 13 to Dec. 15, 2012, with the biggest reinjection rate of 70 m^3/h, accompanying the highest water level increase in reinjection well of 28.65 m, and the highest water level increase in production well of 3.55 m.

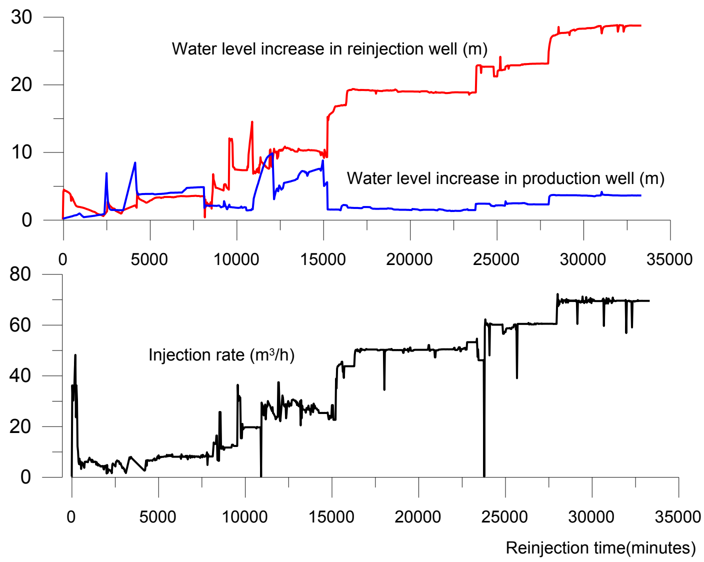


Figure 11: Reinjection rates variations vs water level increases in production and reinjection wells over the period of Oct. 13-Dec. 15, 2012

5.1 Correlation between reinjection rates and water level increases

The reinjection occurs at natural conditions, without artificial pressure. From Table 1 and Figure 12, it can be seen that the reinjection rates are in proportion to the water level increases, with the equation of correlation as follows:

$$y = -0.0468x^3 + 0.861x^2 - 0.7719x + 3.23 \quad (R^2 = 0.9913)$$

Table 1: Reinjection rates vs water level increases

Reinjection rate (m^3/h)	Water level increase (m)
7.8	3.49
11.5	4.49
19.5	7.27
25.1	10.22
43.51	16.82
50	19.04
60.26	23
69.3	28.66

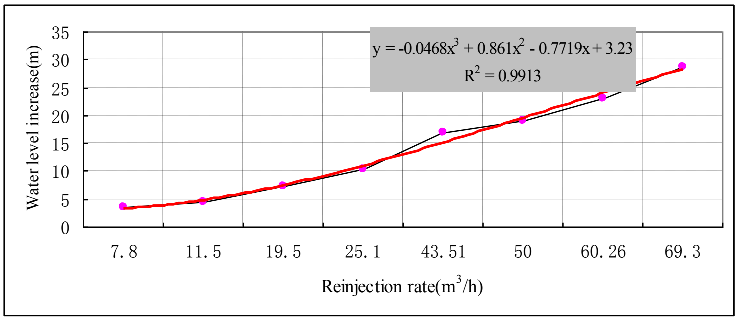


Figure 12: Relationship of reinjection rates vs water level increases (Black line: measured data, red line: fitted data)

5.2 Correlation of water temperatures between reinjection and production wells

In the experiment from Oct. 13 to Dec. 15, 2012, the temperatures of reinjection water were similar to that of the production well, ranging from 50 to 52 ^{0}C; therefore, the influence of reinjection water on the production water can not be found. Especially, if cooling of the production well, or cold-front breakthrough can not be determined. For the purpose of solving this issue, and also testing the long term effectiveness of reinjection, the second reinjection experiment has been implemented in the entire space heating period from Nov. 14, 2013 to Mar. 14, 2014. It shows obviously in Figure 13 that the reinjection water, with the temperatures varying from 30 to 32 ^{0}C, has no influence on water temperatures of 53 ^{0}C in production well for an entire space heating period of 120 days in North China.

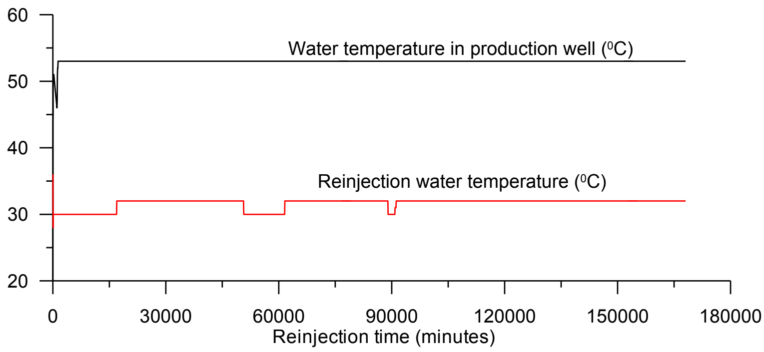


Figure 13: Contrast of reinjection water temperatures to those in production well over the period from Nov. 14, 2013 to Mar. 14, 2014

6. CONCLUSIONS

(1) Reinjection of thermal waste 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) In order to overcome 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 a precision of 3-5 µm, gas venting, back flushing when the pressure difference between the two sides of filtering equipment reaches 50-60 kPa; and re-pumping for the reinjection well at an interval of reinjection for 7 days.

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

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