Clogging mechanism in the process of reinjection of used geothermal water: A simulation research on Xianyang No.2 reinjection well in a super-deep and porous geothermal reservoir

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Abstract: In the process of geothermal exploitation and utilization, the reinjection amount of used geothermal water in super-deep and porous reservoir is small and significantly decreases over time. This has been a worldwide problem, which greatly restricts the exploitation and utilization of geothermal resources. Based on a large amount of experiments and researches, the reinjection research on the tail water of Xianyang No. 2 well, which is carried out by combining the application of hydrogeochemical simulation, clogging mechanism research and the reinjection experiment, has achieved breakthrough results. The clogging mechanism and indoor simulation experiment results show: Factors affecting the tail water reinjection of Xianyang No. 2 well mainly include chemical clogging, suspended solids clogging, gas clogging, microbial clogging and composite clogging, yet the effect of particle migration on clogging has not been found; in the process of reinjection, chemical clogging was mainly caused by carbonates (mainly calcite), silicates (mainly chalcedony), and a small amount of iron minerals, and the clogging aggravated when the temperature rose; suspended solids clogging also aggravated when the temperature rose, which showed that particles formed by chemical reaction had a certain proportion in suspended solids.

Keywords: Xianyang; Super-deep and porous geothermal reservoir; Reinjection; Clogging mechanism

Introduction

Energy and environmental protection is the theme of human survival and development. Given the background of climate change, energy saving, emission reduction, seeking new renewable energy, increasing shortage of fossil energy, greenhouse effect, haze and other environmental problems, geothermal resources, as a kind of clean energy, have been gradually paid attention to by various fields (LIU Jiu-rong, 2003). China has rich super-deep and porous geothermal reservoirs, which are of great potential for exploitation. It is one of the effective ways to relief energy crisis and deal with environmental pollution in China. Since 1980s, the development and utilization of underground hot water in large and medium cities such as Tianjin, Beijing, Xianyang and Xi'an have been gradually rising, which was remarkably conductive to the environment and economy. However, excessive development will inevitably lead to continuous declination of water level, imbalance of waters, increasing cost of water utilization, and changes of geothermal reservoir. Besides, directly discharging the tail water that is of high temperature and salt after heat exchange will exacerbate pollution of river and the environment. In recent years, domestic and foreign research results showed that the artificial reinjection of geothermal water is one of the most effective measures to solve these problems. However, many reinjection practices in domestic

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and foreign geothermal fields showed that clogging occurred during reinjection in most reinjection wells of super-deep and porous geothermal reservoir, which impeded reinjection process and even made some reinjection wells decommissioned (Herman Bouwer, 1991). Therefore, reinjection well clogging remains a big problem highly concerned by academic circles and authorities both at home and abroad. Thus, to study on the reinjection of geothermal water in super-deep and porous reservoir by applying a combined method of hydrogeochemical simulation, clogging mechanism research and reinjection experiment is very important and urgent.

1 An overview of the research area

The research area is located in the northern part of Xianyang City, Shaanxi Province, of which the geographical coordinates are 108°4′E-108°45′E and 34°21′N-34°24′N and the total area is 26.5 km^2. It was the main working area to conduct reinjection experiment in the research, so it was also called reinjection area. Reinjection well No. 2 is located in the east of Shaanxi Institute of Finance, and 240 m north of Wenlin Road. It is located in 108°41′53.7″E, 34°21′31.1″N with an elevation of 420 m. The research area has 5 geomorphic types including the flood plain of Weihe River, 1st, 2nd, and 3rd terraces and loess Tableland area of Wuling Tablel and (LI Pei-yue *et al*. 2014; WU Jian-hua and SUN Zhan-chao, 2016). This research was mainly conducted in the north bank of the Weihe River, which is low in southeast and high in northwest and inclined to the river valley like stair steps. The reinjection area is mainly located in the 2nd terrace of the Weihe River, which is in Xianli fault terrace, one of 6 sub-structural types in Guanzhong Basin, which is located in the middle and lower reaches of the Weihe River (Fig. 1).

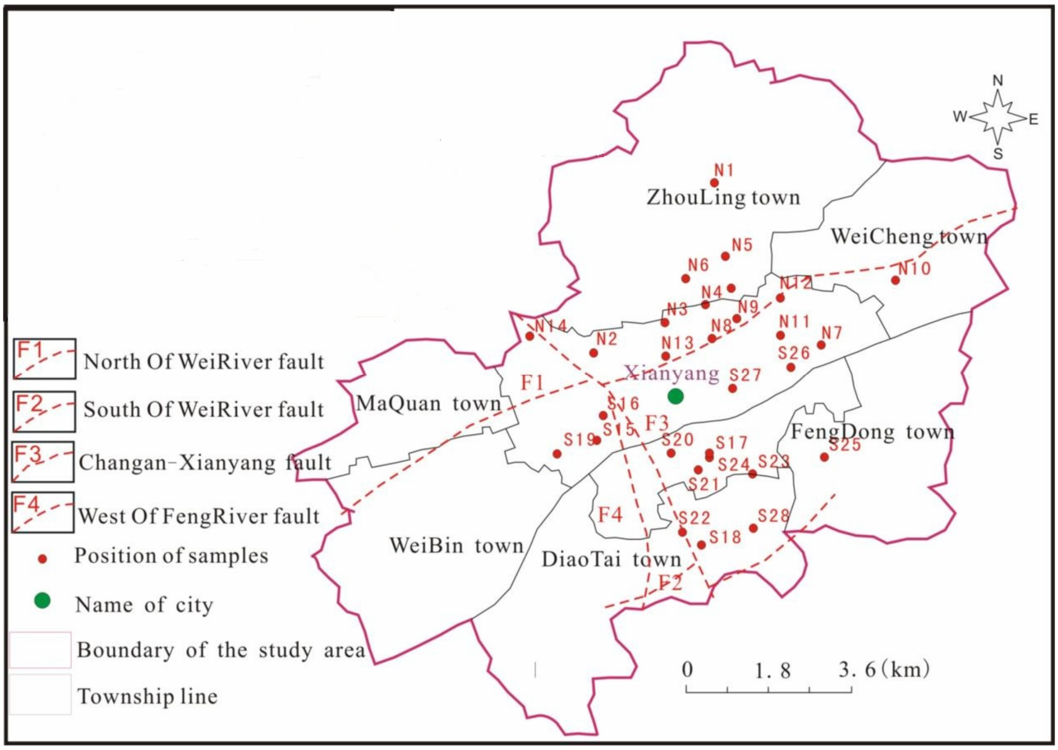


Fig. 1 Geography and location map of the research area

Xianli fault terrace consists of the slope area of Qian County and the hillock area in the south, with an area of about 3 000 km^2. Its foundation bed consists of lower Paleozoic Cambrian and Ordovician clastic stratums, and carbonate stratum, which is overlain by Neogene clastic stratum and Quaternary soft sedimentary stratum. From north to south, Neogene clastic stratum becomes thinner, with a maximum thickness of about 3 000 m. At present, the main reservoir targets of geothermal fluid development and utilization in Guanzhong Basin are Zhangjiapo reservoir group, Tianbahe reservoir group and Gaoling reservoir group in Xianli fault terrace and Xi'an depression (Fig. 2). In this paper, reinjection well WH2 has a depth of 2 700 m, of which the main reinjection stratums are in Lantian Bahe River reservoir group and Gaoling reservoir group: With a depth of 1 415.60-2 656.50 m; a total thickness of 1 240.90 m; 112 sand stratums, as thick as 412.90 m; the average stratum thickness of 3.69 m; porosity of 14.65%-26.59%; and permeability of 4.31-212.28 md. Between the 2 groups, LantianBahe River reservoir group is the main geothermal fluid stratums in reinjection area, and production wells and reinjection wells are mainly located here. For this group, the stratum thickness is generally 855-1 066 m; sandstone thickness 176-437 m; sand-stratum thickness ratio 21.31%-44.67%. This group consists of sandstone and shale interbeds, of which the sandstone is mainly middle-fine sandstone in gray and white. The main components of sandstone are quartz, feldspar and a small amount of debris and argillaceous cement. The content of argillaceous cement in sandstone is generally 8%-21%, with an average of 15%, which indicates that sandstone in Lantian Bahe River reservoir group has a relatively high purity. In conclusion, the research area of Lantian Bahe River reservoir group is widely covered, stable and of good physical properties, large thickness, and moderate depth, all making it most potential geothermal reservoir in Xianyang City.

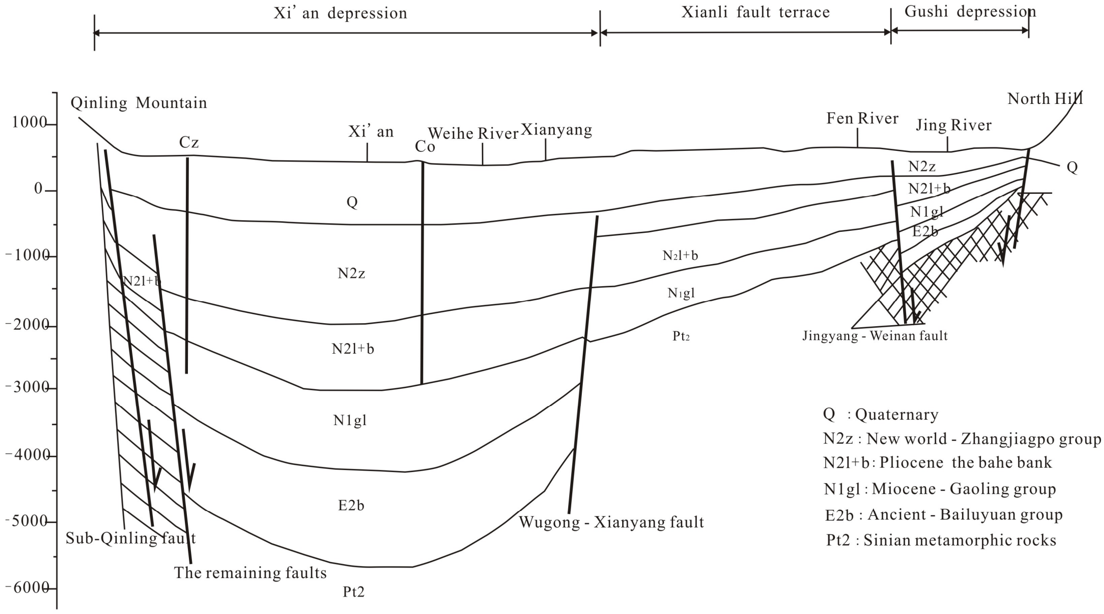


Fig. 2 Profile map of Xi'an depression and Xianli fault terrace

2 Simulation and calculation of temperature of geothermal reservoir

2.1 Geothermometer method

Geothermal water and minerals in geothermal stratums are in chemical equilibrium at a certain temperature, thus the temperature of thermal reservoir can be estimated by geothermometer method. In general, there are two types of geothermometers (HU Yang *et al*. 2009): One is the ratio of components including two or more than two kinds of solutes, such as Na-K geothermometer and K-Mg geothermometer; the other is the absolute concentration of a solute, such as quartz geothermometer. The estimated temperature of geothermal reservoir in production wells and reinjection wells by using quartz geothermometer, chalcedony geothermometer, cristobalite geothermometer, Na-K geothermometer, Na-K geothermometer, and K-Mg geothermometer are listed in Table 1. The calculation results estimated by chalcedony geothermometer method, cristobalite geothermometer method, Na-K geothermometer method, and K-Mg geothermometer method were lower than the actual wellhead temperature, thus all the methods above were not suitable for estimating the temperature of the geothermal reservoir in the research area. The calculation result of Na-K geothermometer was higher than the actual temperature, and the trend of estimated temperature poorly fitted the trend of actual temperature in wellhead, therefore Na-Kl geothermometer method was not the most suitable for the research area. The calculation results showed that the temperature estimated by quartz geothermometer methods was 15-25 ℃ higher than the actual temperature in wellhead, and the results based on saturation index showed that quartz could keep balance, so quartz geothermometer methods were more suitable for estimating the temperature of geothermal reservoir in the research area. The average temperature of the two quartz geothermometer methods were as follows: Production well WR7 was 92.5 ℃, while No. 2 reinjection well WH2 was 99.9 ℃.

2.2 Graphic method of multiple mineral solubility equilibrium

Graphic method of multiple mineral solubility equilibrium considers the relationship between the precipitation and dissolution of minerals and temperature. Its principle is as follows: If take the dissolution state of multiple minerals as a function of temperature, when these minerals at the same time reached solubility equilibrium at a certain temperature, it may be considered that geothermal water and the minerals reached equilibrium, and the temperature of equilibrium is the temperature of geothermal reservoir. This method considers the temperature, redox environment, the mixing of low-temperature water, the escaping conditions of CO_2, and dissolution and precipitation of each mineral and effectively predicts the temperature of geothermal reservoir.

PHREEQC program was used to calculate the saturation index of different minerals in geothermal reservoir at different temperature (Fig. 3a, 3b). Fig. 3a shows the relationship between the precipitation and dissolution of minerals and temperature in the initial condition, of which the equilibrium temperatures of the minerals are low and scattered.

Given that the changes of pressure, temperature and redox environment as well as the escape of CO_2 and the mixing of cold water during sampling process could break the solubility equilibrium thus the equilibrium temperature could not objectively reflect the geothermal state in the initial condition, the simulated results have been corrected and showed by Fig. 3b. In the process of correction, it has been found that the major factors that affecting mineral saturation index were the escape of CO_2 and the mixing of cold water. By using quartz geothermomoeter methods and Graphic method of multiple mineral solubility equilibrium, the temperatures of production well WR7 and No. 2 reinjection well WH2 were both estimated as about 100 ℃ (Table 2).

3 The research on the clogging mechanism

Based on the component identification of rock core, scale samples, and suspended solids and quality analysis of water samples, laboratory simulation experiments of suspended solids, velocity sensitivity, chemical clogging, gas clogging and microbial clogging were carried out. The experiments used the geothermal water sample of WH2, tail water sample of WR7, and rock core sample taken from 1 976.35-2 115.35 m sandstone stratum in Lantian Bahe River reservoir group of WH2.

The main indoor simulation experiment device (high-temperature, high-pressure, and multi-function core displacement device) used in this research is shown in Fig. 4.

Table 1 Estimated temperature of geothermal reservoir by using different geothermometer (℃)

Sampli-ng well	Actual tempera-ture (℃)	Quartz geothermo-meter (without steam loss)	Quartz geothermo-meter (with maximum steam loss)	Chalcedony geothermom-eter	Cristobalite geothermo-meter	Na-K geotherm-ometer	Na-K1 geothermo-meter	K-Mg geothermo-meter
WR7	76	91.4	93.5	60.7	41.2	70.4	132.6	48.5
WH2	76	99.3	100.4	69.2	49.0	51.3	114.3	41.5

Table 2 Actual temperature and temperature estimated by two methods (℃)

Sampling well	Actual temperature (℃)	Quartz geothermometer (without steam loss)	Quartz geothermometer (with maximum steam loss)	Graphic method of multiple mineral solubility equilibrium
WR7	76	91.4	93.5	100.0
WH2	76	99.3	100.4	100.0

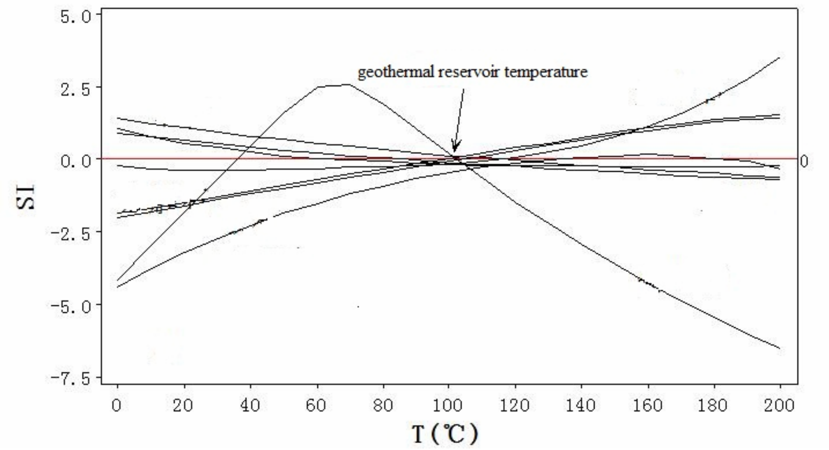


Fig. 3a SI-T graph of the production well

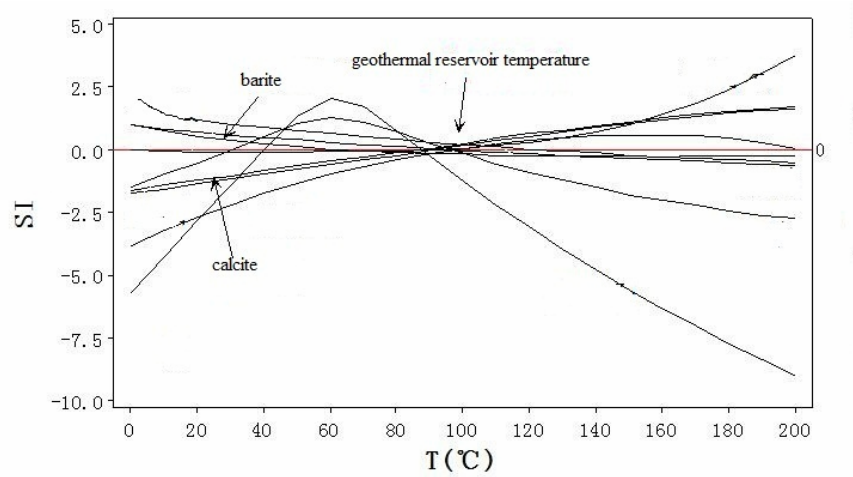
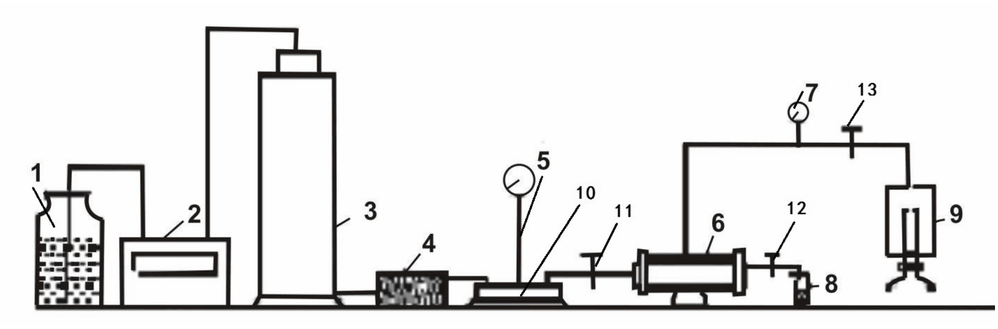


Fig. 3b SI-T graph of the reinjection well

Fig. 4 Core displacement device of indoor simulation experiment



1 - Pressure transmitting medium; 2 - Micro pump; 3 - Intermediate container; 4 - Filter; 5, 7 - Pressure gauge; 6 - core holding holder; 8 - Measuring cylinder; 9 - Pressure pump; 10 - Heater; 11 - No.1 valve; 12 - No.2 valve; 13 - No.3 valve

Fig. 5 The process of core flow test

The working process of the indoor simulation experiment device is shown in Fig. 5.

1) Working principle of the core displacement device: Inject the water sample into intermediate container (3). While maintaining the experiment conditions as constant, measure the initial permeability K_0 of saturated core in water sample by core holder (6). After the displacement time t, measure permeability K of core. The clogging rate: $(K_0\text{-}K) /K_0$ (MA Zhi-yuan *et al*. 2013).

2) The adjustment of pressure in the experiment: The experiment displacement pressure is adjusted by the constant-flux pump (2), and the confining pressure of the core is adjusted by the ring section pump (9).

3) The adjustment of temperature in the experiment: Put the experiment pipelines and device part 3-6 in the electric thermostat to adjust the temperature required for the core displacement experiment.

4) The adjustment of flow velocity in the experiment: The fluid velocity of the core displacement experiment is adjusted by the constant-flux pump (2).

3.1 Suspended solids

Suspended solids clogging is one of the most common clogging type. Besides the suspended solids carried by tail water, precipitation in chemical reaction, particles produced by velocity sensitivity and microbial accumulation also accounted for a considerable proportion of suspended solids (LAURA M McDowell-Boyer *et al*. 1986).

The depth of the target stratums in the reinjection research is 1 415.60-2 656.50 m, with a thickness of 1 240.9 m, which are mainly located in Lantian Bahe River reservoir group and Gaoling reservoir group. The rock cores were taken from two pieces of sandstone in different depth, which mainly consist of fine sandstone and siltstone. And the cores were numbered as 2-1 and 10-2. Their porosities were 12.17% and 3.47% and permeabilities were 21.57 md and 0.116 md respectively. The mineral compositions of these two sandstone samples were identified respectively.

The results of X diffraction of siltstone (Fig. 6 and Table 3) showed that the major minerals of rock cores in reinjection area were quartz, calcite and plagioclase. In the core 2-1, aluminosilicate including quartz and plagioclase accounted for 84.3%; calcite only 13.8%; and clay mineral 3%. In core 10-2, aluminosilicate including quartz and plagioclase accounted for 65.75%; calcite 31.2%; clay mineral 1.5%. The two cores had quite different properties and small particle size, which could lead to relatively low permeability, so they were different from the actual rock cores in geothermal reservoir. Therefore, the analysis results were also different from actual condition and they are for reference only.

The results of laboratory simulation experiments are shown in Table 4. With temperature increasing, (suspended solids + chemical) clogging rate increased. Both suspended solids clogging and chemical clogging rate increased with the increase of temperature, because when temperature increased, carbonates and silicates such as chalcedony precipitated as suspended solids, which formed a synergistic effect.

The reinjection practice showed: The depth of reservoir that suspended solids entered and the quantity of suspended solids depend on the matching condition of solid particles diameter and the throat diameter of the reservoir, which is called the law of "1/3-1/7" (HE Guo-jian and YANG Xu, 2008). According to the analysis results of suspended particle size and the physical properties of the reservoir, the diameter of suspended solids in the tail water and throat diameter measured by mercury intrusion method are listed in Table 4: Suspended solids that have the diameter distributing within "1/3-1/7" of throat diameter are the major cause of suspended solids clogging, and also suspended solids that require attention in filtration process of tail water. As shown in Table 5, in order to reduce suspended solids clogging, it is recommended to choose the lower limiting value of 1/3-1/7 (1.25 m-2.91 m), 1.25 μm, to be as the filtration level. However, because the core of WH2 was relatively loose, yet the sample was relatively dense and cemented, so its permeability was low and the median throat radius was small, which cannot fully represent the core permeability of WH2. Therefore, it is recommended to select 2 μm-level filter for suspension filtration, so as to achieve better filtration effect.

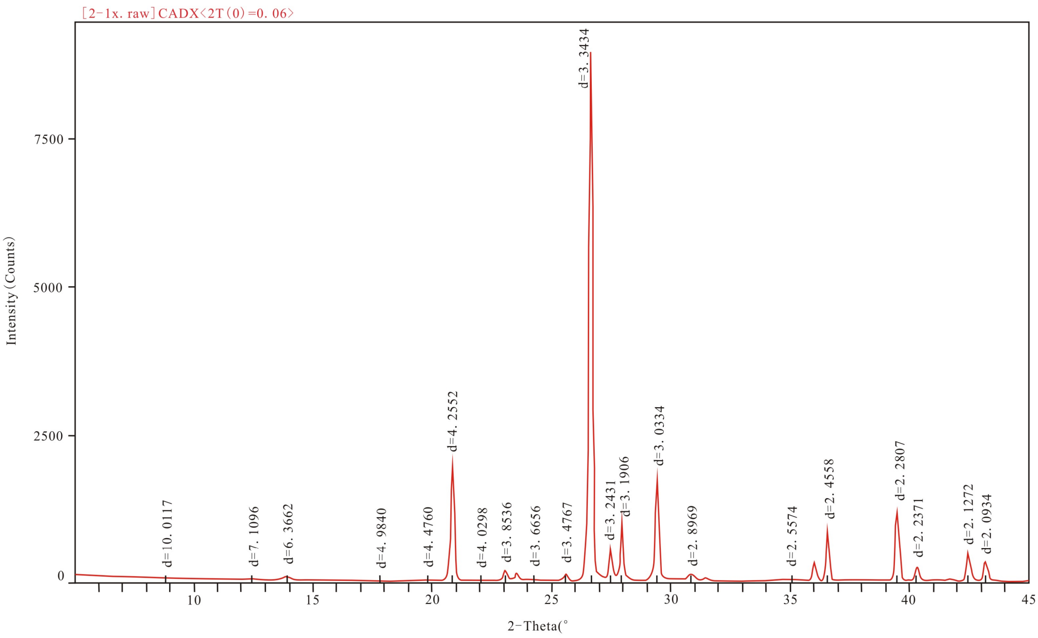


Fig. 6a X diffraction pattern of the fine sandstone sample 2-1

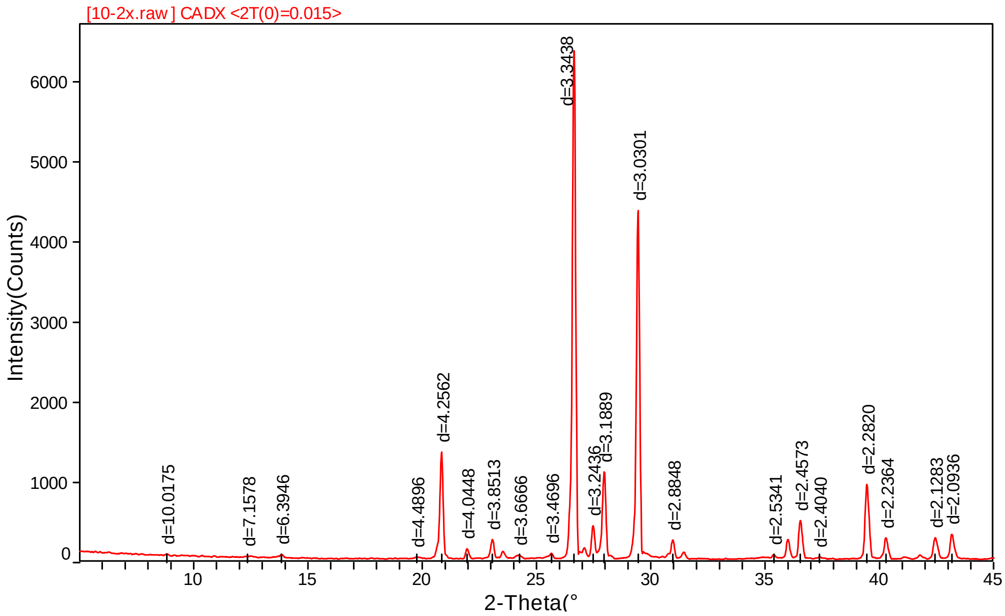


Fig. 6b X diffraction pattern of the fine sandstone sample 10-2

Table 3 X diffraction results of the samples from the reinjection well

Sample	Quartz	Plagioclase	Potassium feldspar	Calcite	Ankerite	Montmorillonite	Illite	Chlorite	Kaolinite
2-1	61.6	12.3	7.4	13.8	1.9	1.0	1.0	1.0	/
10-2	45.1	14.2	5.4	31.2	2.6	/	0.5	/	1.0

Table 4 Results of core clogging test at different temperatures (%)

Clogging rate	30 ℃	50 ℃	70 ℃
Suspended solids + chemical clogging	15.82	25.00	27.87
Chemical clogging	12.50	14.40	15.30
Suspended solids clogging	3.32	10.60	12.57

Table 5 2-7 Core pore throat diameter statistics

Pore throat diameter	>1/3 (>2.91 μm)	1/3-1/7	<1/7 (<1.25 μm)
Proportion (%)	75.11%	10.1%	14.79%

According to the removal rates (Table 6) of suspended solids at different filtering levels, when using 2 μm-level filter, the suspended solids that were less than 2μm averagely accounted for 20.67%, which means the removal rate of the suspended solids was 79.33%; when using 3, 4, 5 μm-level filter, the removal rates of the suspended solids were 72.88%, 68.29%, 65.75% respectively. Therefore, for 3, 4, 5 μm-level filter, the removal rates of 2 μm-level suspended solids were 6.45%, 11.04%, and 13.58% respectively. In conclusion, using 2 μm-level filter would greatly alleviate the effect of suspended solids clogging in the process of reinjection.

Table 6 Removal rate of suspended solids at different filtering levels (%)

Filtering level	Proportion of suspended solids	Removal rate of suspended solids	Increment of removal rate
<2 μm	20.67	79.33	/
<3 μm	27.12	72.88	6.45
<4 μm	31.71	68.29	11.04
<5 μm	34.25	65.75	13.58

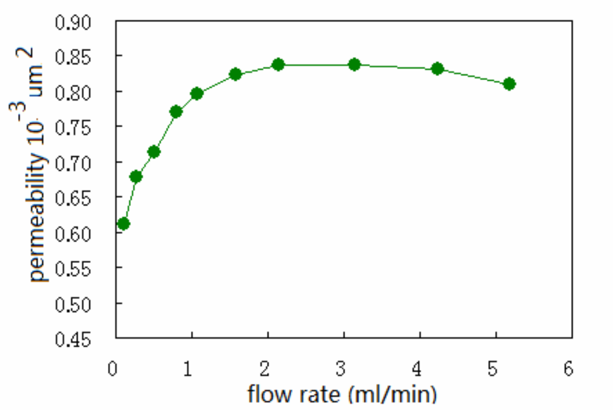


Fig. 7 Results of velocity sensitivity experiment of core 2-7

3.2 Particle migration

The influence of particle migration can be measured by velocity sensitivity experiment. Specifically, changing the flow velocity of water in core displacing experiment can measure permeability changes of rock sample, so clogging caused by particle migration can be evaluated (CHEN Long-long and WANG Wei-bo, 2015; SHI Jing-ping *et al*. 2003; DUAN Yong, 1994). The results of velocity sensitivity experiment of raw geothermal water are shown in Fig. 7. According to Fig. 7, the permeabilities of core 2-7 that were caused by velocity sensitivity increased to different extent. The results showed that the clogging of WH2 was not affected by velocity sensitivity effect. Instead, its permeability increased with the increase of reinjection velocity. Such phenomenon lasted through the whole displacement experiment, which indicated that high reinjection velocity would not cause clogging even to some extent improved the reinjection effect.

3.3 Indoor chemical clogging simulation experiments

3.3.1 Simulation of the mixing of used and raw geothermal water

In order to make clear the process that used geothermal water entered reservoir stratum, mixed with raw water and had a chemical reaction, which produced mineral precipitation, the research on the mixing of tail water from WR7 and raw water from WH2 in different proportion has been carried out by using PHREEQC program. The ratio 10:0 simulated the whole process of chemical reaction of raw water, while the ratio 0:10 simulated the chemical reaction of tail water before mixing with raw water. Fig. 8 shows the total amount of precipitation when tail water and raw water mixed in different proportion. As the proportion of tail water increased, the total amount of precipitation gradually decreased, which was obviously affected by the temperature.

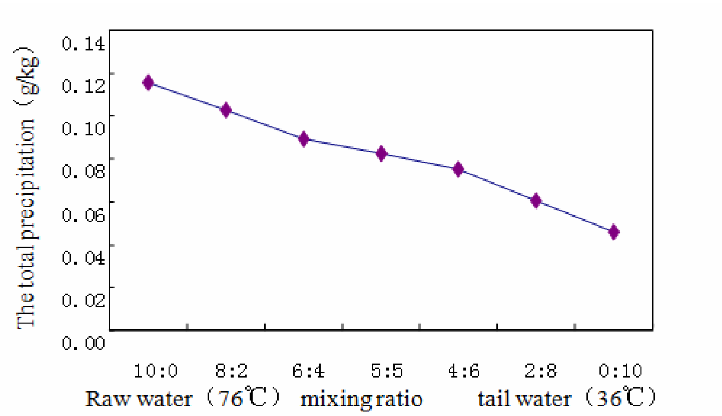


Fig. 8 Total amount of precipitation when tail water and raw water mixed in different proportion

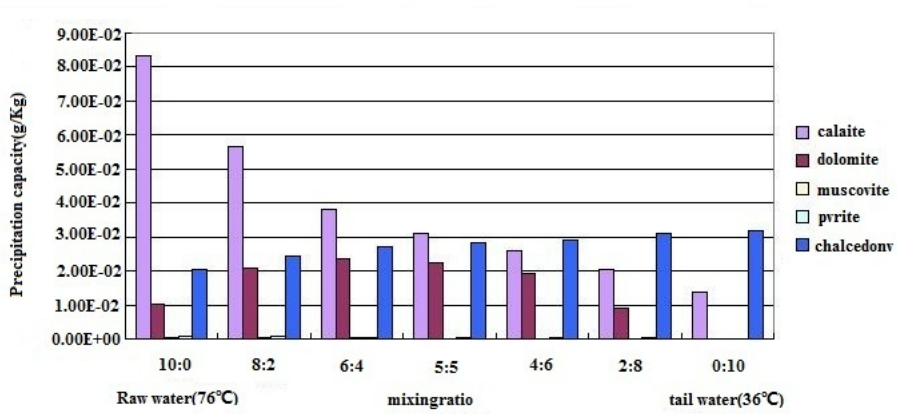


Fig. 9 Precipitation amount of different minerals when raw water and tail water mixed in different proportions

Fig. 9 shows the precipitation amount of different minerals when raw water and tail water mixed in different proportions. The precipitation amount of calcite reached maximum at the beginning, but with the proportion of tail water increasing, its precipitation amount gradually decreased. The precipitation amount of chalcedony increased with the proportion of tail water increasing. The precipitation amount of dolomite increased first and then decreased. Other minerals' precipitation amount was too small to be considered. In conclusion, in the process of reinjection, major precipitation minerals were calcite, chalcedony, dolomite, and a small amount of pyrite, while white mica content was very small.

3.3.2 Indoor core experiments

In order to quantificationally make clear the permeability changes of rock cores after tail water entered reservoir stratum and had chemical reaction with rock core, experiments were carried out at the same flow rate. With keeping other conditions the same while changing the temperature only, indoors core experiments were carried out at 30 ℃, 50 ℃ and 70 ℃.

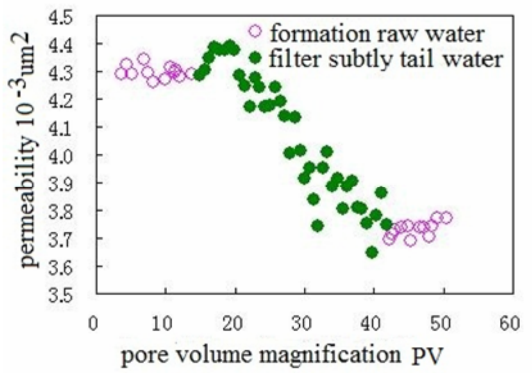


Fig. 10 Results of core displacement experiment for chemical clogging at 30 ℃

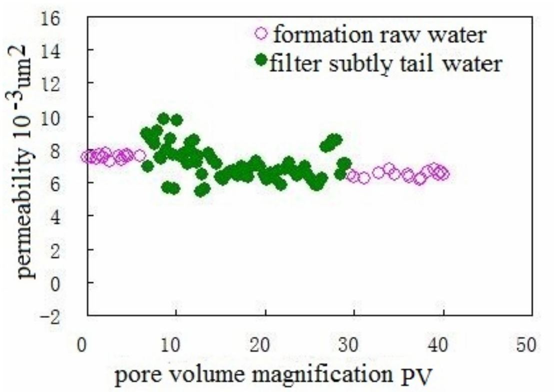


Fig. 11 Results of core displacement experiment for chemical clogging at 50 ℃

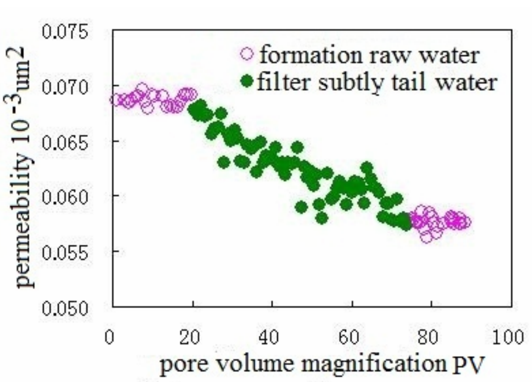


Fig. 12 Results of core displacement experiment for chemical clogging at 70 ℃

Table 7 Results of microbial tests in Xianyang geothermal wells (a/ml)

Sample	Saprophytic bacteria	Iron bacteria	Sulfate-reducing bacteria
Tail water of WR7	1.1×10^4	4.5×10^2	0
Raw water of WH2	0	0	0

1) Experiment results at 30 ℃

The results of core displacement experiment at 30 ℃ (Fig. 10) showed that the original permeability of the core K_0 30 ℃= 4.285×10^{-3} μm^2. After using tail water for displacement for 39 PV, the permeability of the core K_1(tail water)=3.751×10^{-3} μm^2. At this time, when using raw water to have the experiment, the permeability of the core K_d=3.748×10^{-3} μm^2. When using finely filtered water for displacement at 30 ℃, the clogging rate was 12.5%.

2) Experiment results at 50 ℃

The results of core displacement experiment at 50 ℃ (Fig. 11) showed that the original permeability of the core K_0 30℃=7.542×10^{-3} μm^2. After using tail water for displacement for 20 PV, the permeability of the core K_1 (tail water) = 6.536×10^{-3} μm^2. At this time, when using raw water to have the experiment, the permeability of the core K_d=3.748×10^{-3} μm^2. When using finely filtered water for displacement at 50 ℃, the clogging rate was 14.2%.

3) Experiment results at 70 ℃

The results of core displacement experiment at 70 ℃ (Fig. 12) showed that the original permeability of the core K_0 30 ℃=0.0678×10^{-3} μm^2. After using tail water for displacement for 70 PV, the permeability of the core K_1 (tail water)= 0.0596×10^{-3} μm^2. At this time, when using raw water to have the experiment, the permeability of the core K_d=0.0573×10^{-3} μm^2. When using finely filtered water for displacement at 70 ℃, the clogging rate was 15.3%.

In conclusion, with the increase of temperature, chemical clogging aggravated. The results of hydrogeochemical simulation and indoor core displacement experiments combined showed that the major minerals that caused chemical clogging of Xianyang No.2 reinjection well were carbonates and silicates such as chalcedony.

3.4 Gas clogging

Gas clogging mainly occurred at the beginning of reinjection process. When injecting tail water into the bottom, the hydrodynamic conditions get worse, the pressure tends to be constant, and the bubbles are more likely to remain in porous intermediaries. When the head pressure of reinjection water $P_1\approx P_2$ (Fig. 14), airlock is formed, which can further cause gas clogging (LIN Jian-wang and ZHAO Su-min, 2010). In order to quantitatively make clear gas clogging condition and its changes, we have conducted water-gas displacement experiments. Fig. 13 shows the experiment results. According to Fig. 13, the initial permeability of core K_0=0.0024×10^{-3} μm^2. After the first gas displacement experiment, the permeability of core K_{d1}=0.0015×10^{-3} μm^2, and the clogging rate was 37.5%. After the second gas displacement experiment, K_{d2}=0.00147×10^{-3} μm^2, and the clogging rate was 38%, which kept almost unchanged. It should be noted that the gas clogging simulation experiment used nitrogen to displace saturated raw water until there was only bound water left, and used formation water to measure permeability. Then repeated in this way. The gas clogging rates worked out under such experimental conditions were the largest gas clogging rates in an ideal geothermal reservoir, thus 37.5% larger than actual rate.

The results showed that some gas remained in the core pores so that they were difficult to be filled by reinjection water, which caused gas clogging. In the process of reinjection, the larger bubbles were discharged or decomposed into smaller bubbles through water flowing. Therefore, the larger bubbles were difficult to enter the reservoir. The major cause of gas clogging was the bubbles which had the same diameter with the throat of the stratum. According to the experimental results, the gas clogging rate was 10% larger than that in Xianyang No.1 reinjection well at the same temperature, which means gas clogging was more likely to occur in Xianyang No.2 reinjection well. Of course, the experimental results were related to permeability and the porosity and permeability of the core in Xianyang No.2 reinjection well were far less than those in Xianyang No.1 reinjection well. With the reinjection of tail water, the temperature will exceed 50 ℃, the experimental temperature. The higher the temperature is, the greater the pressure will be, which can further increase the solubility of gas so as to lower the gas clogging rate. In order to reduce gas clogging, the leakproofness in the process of production, transportation and reinjection must be maintained and the exhaust equipment shall be used.

3.5 Microbial clogging

The microbial clogging state depends on the type, amount, and environment of the bacteria. The results of core displacement experiments by using tail water before and after sterilization are shown in Fig. 15 and Fig. 16. According to the research on WH2, the major bacteria caused clogging were saprophytic bacteria, iron bacteria and sulfate-reducing bacteria. The microbial experiment results of raw water from WH2 and tail water from WR7 are shown in Table 7.

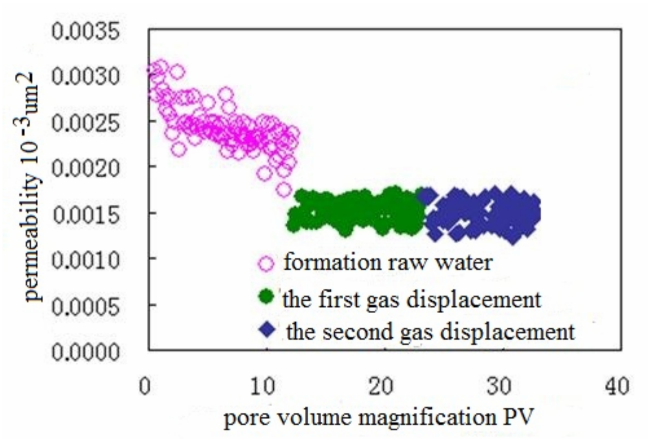


Fig. 13 Results of core displacement experiment for gas clogging

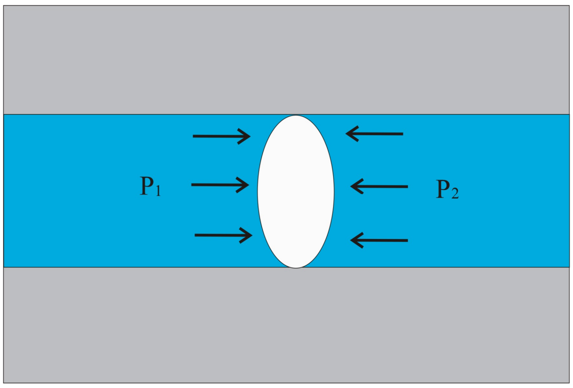


Fig. 14 Airlock sketch map

According to Table 7, tail water in WR7 had high contents of saprophytic bacteria and iron bacteria, while no sulfate reducing bacteria have been detected. Under the reinjection conditions of WH2, the major bacteria in the reinjection area were saprophytic bacteria, supplemented by iron bacteria, and sulfate reducing bacteria were few or absent. But in the raw water of WH2, there has been no saprophytic bacteria, iron bacteria or sulfate reducing bacteria detected. The possible reason was that Xianyang No.2 reinjection well has just operated for a short time without being through the stopping period, which was shorter than the breeding time of saprophytic bacteria, iron bacteria and sulfate reducing bacteria. With the operation of reinjection wells, the bacteria content will increase. In order to quantitatively make clear the state of bacterial clogging, this research conducted a simulation experiment of bacterial clogging. By using two pieces of similar cores 2-8 and 2-9 to conduct core displacement experiment at 70 ℃, the results worked out are as follows: The original permeability of core K_0=12.31 md; after using finely filtered water in core displacement experiment of core 2-8 for 50.2 PV, the permeability of core K_1(tail water) =11.71 md; and then used raw water in core displacement experiment, and the permeability of core K_d=10.42 md. Aiming at this tail water reinjection of WH2, it is better to choose chlorine dioxide or sodium hypochlorite and combine it with ultraviolet ray for the disinfection of tail water. This method is effective, space-saving, and cost-saving. But when the concentration of disinfectant is too high, the quality of tail water can be affected. In addition, ultrafiltration membranes can be used to filter out bacteria. This method does not affect water quality, but it has a big cost and can affect reinjection amount.

3.6 Analysis of major factors causing clogging in reinjection process

According to the results of indoor core displacement simulation experiments, the clogging rates of different clogging types at different temperatures are shown in Fig. 17. With the temperature increasing, the clogging rates of suspended solids clogging and chemical clogging increased, and the chemical clogging rate was higher; the clogging rates of suspended solids clogging and chemical clogging were 3.32% and 12.5% respectively at 30 ℃, between which the major type was chemical clogging; at 50 ℃, the rates increased to 10.6% and 14.4% respectively, while gas clogging became the major type, with a clogging rate of 37.5%. The clogging rate worked out by gas clogging simulation experiments was higher than the actual rate. According to the results of hydrogeochemical simulation of geothermal reservoir, 70 ℃ was the closest to the actual temperature. At 70 ℃, when conducting particle migration and microbial clogging experiments, the chemical clogging rate was still the highest, reaching 15.3%. Suspended solids clogging rate came second as 12.57% while microbial clogging was 11.2%, ranking the third. The results of velocity sensitivity experiments showed no impact of particle migration. Therefore, the major types of the clogging of Xianyang No. 2 well were chemical clogging and suspended solids clogging.

3.7 Field experiments

WR7 is a production well while WH2 is an reinjection well. The closed reinjection of WH2 has been conducted without pressurized condition and the reinjection amount has been monitored. The instantaneous maximum flow rate was 2 976 m^3/d or 124 m^3/h. The target stratum was in Lantian Bahe River reservoir group. The reinjection flow rate was 0.01876 m/d. After the reinjection, the flow rate to keep stable water level was 118 m^3/h, with the reinjection rate reaching 100%. The reinjection equipment is shown in Fig. 18.

In the actual process of reinjection, various clogging types often occur at the same time and interact with each other, and their interaction is extremely complex. At present, the researches on the mechanism of composite clogging are still very scarce. In the above research, the clogging types mentioned above are only the external factors rather than all the factors. The internal resistances of geothermal reservoir including framework contraction, ground pressure, the physical properties and the formation of cold front are also important factors that can reduce the reinjection rate. Therefore, adding PESA antiscale into the equipment can reduce chemical clogging and suspended solids clogging in reinjection process. As for gas clogging, repeated gas displacement experiments can reduce it. And filtering and sterilizing the tail water before reinjection can reduce microbial clogging.

On the basis of the research on the clogging mechanism in reinjection process, the basic factors causing clogging have been preliminarily determined and can be avoided by taking some corresponding measures. Reinjection can lift groundwater levels, achieve sustainable development and use of geothermal energy, and more importantly, reduce the pollution caused by burning coal.

4 Conclusion

1) The major minerals that caused chemical clogging in the process of reinjection were carbonates and silicates such as chalcedony, as well as a small amount of iron minerals. Chemical clogging aggravated when the temperature increased.

2) The maximum gas clogging rate could reach

37.5% in the process of reinjection. As the tail water has been injected into reinjection well, the pressure increased, which further increased gas solubility and lowered the gas clogging rate. In order to reduce gas clogging, the leakproofness in the process of production, transportation and reinjection must be maintained and the exhaust equipment shall be used.

3) At 70 ℃, the microbial clogging rate worked out by core displacement experiments before and after the sterilization of filtered tail water were 15.3% and 4.1% respectively. After the sterilization, the microbial clogging rate decreased by 11.2%, and the relieving rate was 73.2%. The sterilization effect was good. It is better to choose chlorine dioxide or sodium hypochlorite and combine it with ultraviolet ray for the disinfection of tail water.

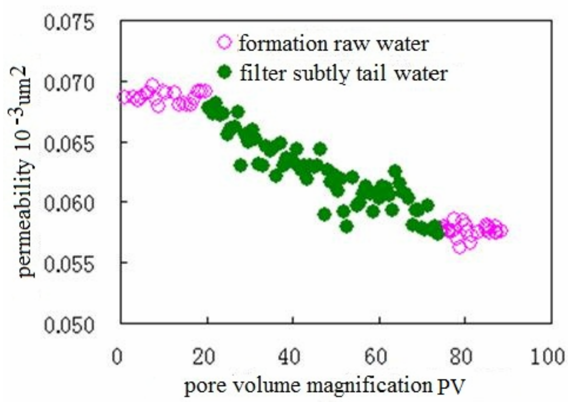


Fig. 15 Results of core displacement experiment before bacterial culture

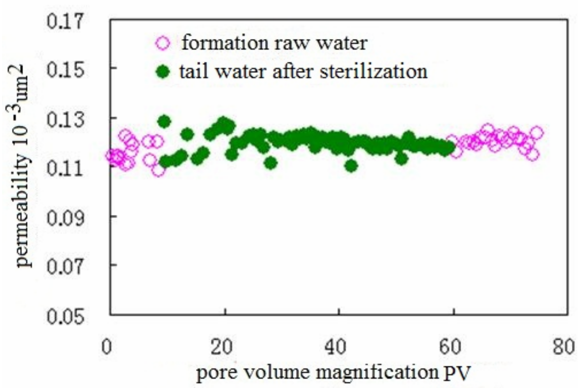


Fig. 16 Results of core displacement experiment after bacterial culture

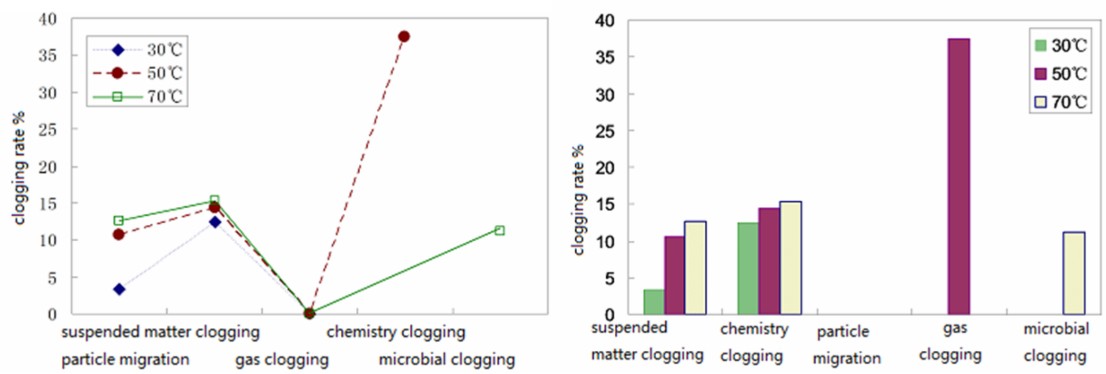


Fig. 17 Comparison among the clogging rates of different clogging types

Fig. 18 Reinjection equipment

4) For reinjection condition, 70 ℃ was the closest to the actual temperature. At 70 ℃, when conducting particle migration and microbial clogging experiments, the chemical clogging rate was still the highest, reaching 15.3%. Suspended solids clogging rate came second as 12.57% while microbial clogging was 11.2%, ranking the third. The results of velocity sensitivity experiments showed no impact of particle migration. Therefore, the major types of the clogging of Xianyang No. 2 well were chemical clogging and suspended solids clogging.

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