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A Case Study Of Heat Depleted Tail Geothrmal Water Reinjection In Sandstone Gerothermal Reservoir

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ABSTRACT

Geothermal energy has been widely using for space heating in northern China to replace coal burning to resolve the severe atmospheric pollution problems there. However after thermal energy been extracted, the tail geothermal water with high salt contents was mostly directly discharged to drainages or rivers, caused surface water pollution and pressure drop of geothermal reservoir. Reinjection of the cooled tail geothermal water back into the reservoir is necessary. The paper introduced a case study of reinjection into sandstone reservoir in a 52,000m^2 space heating program which has been successfully operating for three years. Several key technologies adopted in the practice ,which are (1) Using heat exchanger to shorten the circulation path avoiding air contamination; (2) Coarse and fine two stage filters to remove the suspending solids avoiding physical blockage; (3) Gas deprive instrument to remove the separated gases avoiding gas blockage; (4) Thrust the injection pipe-end deep under well water's surface avoiding air entering; (5) Longer well screen to ensure sufficient injection space; (6) Large diameter borehole with gravel pack to provide a high permeable zone around the screen, while restraining the reservoir rock from collapsing near borehole.

1. INTRODUCTION

Geothermal energy is an indigenous clean supplementary energy, which has been widely using for space heating in northern China. According to a brief survey, there are about 102 million m^2 of space heating projects using geothermal water in northern China[1], which replaces standard coal burning of 2 million tons per year of traditional heating system. There are mainly two kinds of geothermal reservoirs been exploited, which are Palaeozoic and Proterozoic Carbonate geothermal reservoir, Cenozoic sandstone geothermal reservoir, the latter accounts for 60% of total geothermal space heating project. Though great contribution has been made by the utilization of geothermal energy to reduce CO_2 emission, due to mal-management and technological difficulties[2], the heat depleted geothermal tail water was mostly directly discharge to nearby water bodies, because of the usually high salt content of the geothermal water, the discharged tail water has caused surface water pollution. Moreover, the burial depth of the sandstone geothermal reservoirs is greater than 1 000 m in northern China, which made the hot water stay stagnant in the pore space of the reservoir, the withdraw of the geothermal water has caused great pressure dropdown at the reservoir. For example, there is 5~10m /a annual water level drop at Xian geothermal field with a maximum total water level drop of 246.5m at the withdrawal center[3], around 3~4m/a annual water level drop at Tianjing geothermal field[4] and around 8.2m/a of annual water level drop at Dezhou geothermal field(Figure1). To sustainably utilize geothermal energy for space heating, avoiding surface water pollution, reinjection of the cooled tail water back into the geothermal reservoir is necessary. While reinjection into sandstone geothermal reservoir, the problem of fast drop in reinjection rate is inevitably encountered. In order to showcase how to successfully inject the tail water back into sandstone geothermal reservoir and what key technologies related, the paper reviewed a project of a production-reinjection two wells system exploiting Neocene Guantao formation geothermal reservoir, which serves a 52 000 square meters of space heating needs and has been successively operating for three years.

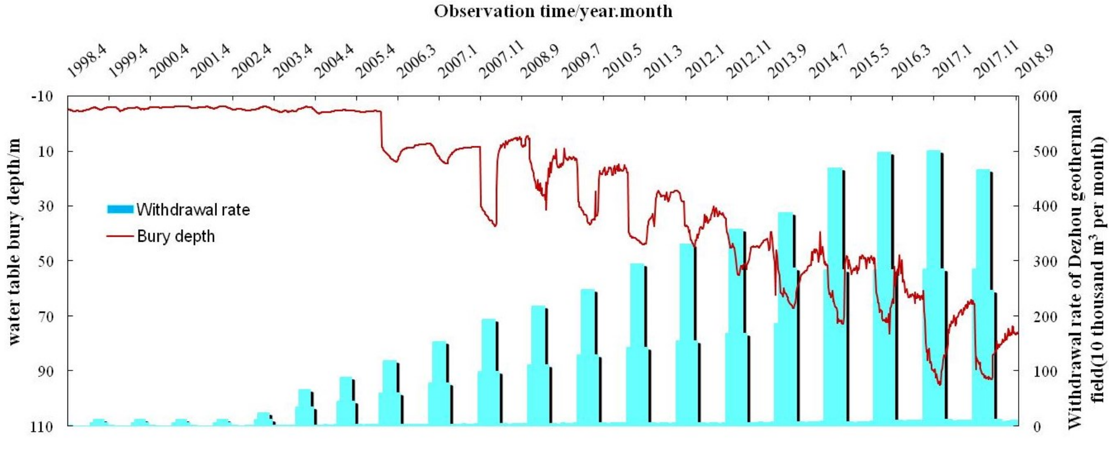


Figure1 The water table bury depth and month withdrawal rate of Guantao geothermal reservoir at Dezhou geothermal field

2. GEOLOGY BACKGROUND OF THE PROJECT

2.1 Tectonic structure

The project locates at the western edge of the Dezhou depression (Figure 2), which is a Mesozoic-Cenozoic sedimentary basin[5], the total thickness of the Cenozoic strata is about 2 000-5 000meters . Gucheng uplift on the west, where the paleogene strata are absent, Neocene Guantao formation is unconformity with Mesozoic strata. Chengning uplift on the south-east, where the Neocene Guantao formation is unconformity with Archean metamorphic strata.

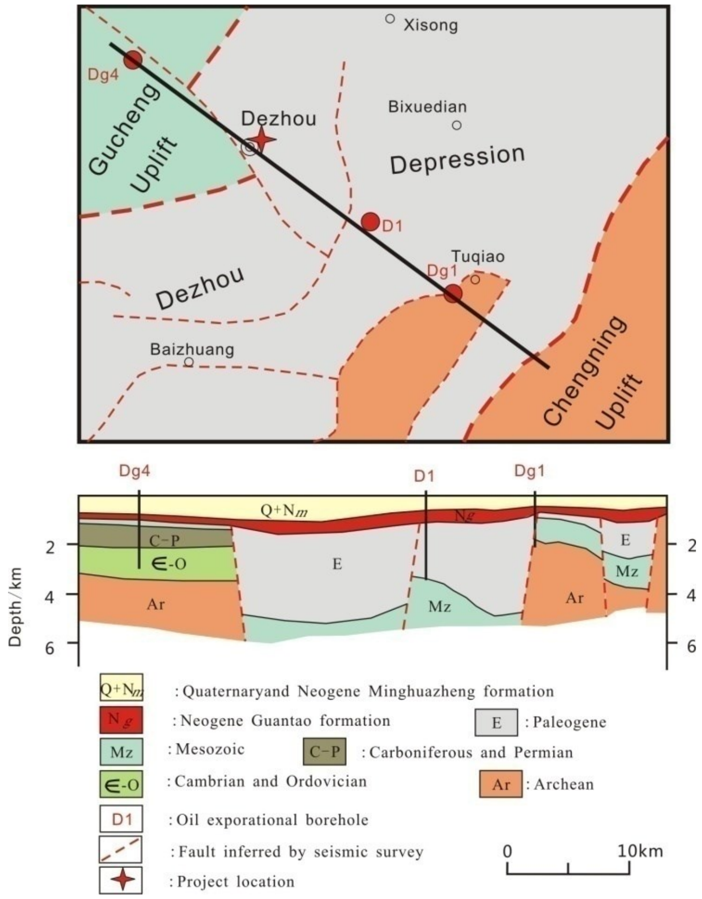


Figure 2 The tectonic structure sketch map and cross-section of the study area

2.2 Regional stratigraphy

Based on the regional survey data, the stratigraphy profile from bottom to top are as follows in the study area:

(1) Archean metamorphic strata: It makes up the crystal basement of the entire region, the rock's lithology is granito-gneiss.

(2) Cambrian –Ordovician carbonate strata: This strata are absent in the Chengning uplift area, and evenly distributed in the Dezhou depression and Gucheng uplift area. The rock's lithology mainly are limestone, dolomite, argillaceous limestone intercalation, the bottom of Cambrian strata are composed of argillaceous shales. The total thickness of the strata is about 1 200m.

(3) Carboniferous-Permian clastic strata: The spacial distribution is the same as that of the Cambrian-Ordovician strata. The rock's lithology mainly mudstone intercalated with sandstone, there are several coal seams, the total thickness of the strata is bout 800m.

(4) Mesozoic strata clastic strata: This strata are absent in the Chengning uplift area, and the strata's thickness is about 160m in the Gucheng uplift area revealed by borehole Dg4, about 1 000m in the Dezhou depression area uncovered by borehole Dg1. The rock's lithology mainly mudstone intercalated with sandstone, there are a few tens meters of pyroclastic tuffs and basalt.

(5) Paleogene clastic strata: This strata are absent in the Chengning uplift and Gucheng uplift area .The strata is thicker in the western part of Dezhou depression. At the eastern part of Dezhou depression, the thickness is about 150m revealed by borehole Dg1 at the uplifted area, and is about 1 200-1 500m in the depressed area.

(6) Neogene Guantao formation: This formation can be divided into two sections based on the rock property, the lower part mainly composed of gravel sand or coarse sand, which is about 160-180m thick, and is the most favorable geothermal reservoir for exploitation, the temperature of the reservoir is about 55℃-62℃. The upper section are mudstone intercalated with fine sandstone, the thickness of this section is 200-300m, which combined together with overlay strata to form the reservoir's cap for heat to retain.

(7) Quaternary and Neogene Minghuazheng formation: The rock's lithology mainly are clay intercalated with fine sand, the total thickness of the strata is about 900-1100m. The thermal gradient is around 3.2-3.4℃/100m in the strata, which makes it an ideal reservoir cap to retain the heat flux originated from the earth's interior. The groundwater contained in the aquifers mainly for industrial agriculture and tap water supple.

3 PROJECT CONFIGURATION

3.1 Wells information

The project has two wells, one for pumping and the other for reinjection. The distance between the pumping well and reinjection well is 172.5m. The pumping well (Pm) was drilled in 1997 with an exploration depth of 1491.37m, and the well casing length is 1479.72m, the diameter of the well casing is 177.8mm, and diameter of the borehole is 224.5mm. The total length of the screen is 72.32m. Using naked screen well construction technology, sealed with three layers of rubber blocks at the top of the screen assembly. The screen is made of perforated steel casing wound with steel wires with 0.75mm gap between each interval; the total porosity of the screen is about 13%(Figure 3). The initial water level of the pumping well is 8.4m above the ground, and well discharge rate is 100m^3/h at 16.4m of drawdown, and the temperature of the geothermal water is 56℃. Since 1998, the pumping well started to withdraw geothermal water for residential and work offices spacing heating in the winter, and provided hot water for one geothermal bath center for the whole seasons, which was closed in 2018. Before 2016, the heat depleted tail water was discharged directly into the city's drainage system, caused some environmental concerns, and there is a rapid water level drawdown in the pumping well (Figure1). To show case how to sustainably exploit the geothermal resource, and to meet the government regulation needs, the institute started to build a sandstone geothermal reservoir reinjection research center and a demonstration project in 2016.

The reinjection well (Re) was drilled in 2016, the exploration depth of the borehole is 1544.50m, and well depth is 1536.44m. The diameter of the well casing is 177.8mm, and diameter of the borehole is 450mm at the screen section. The total length of the screen is 169.58m (Figure3). The screen configuration is the same as that of the pumping well. using gravel packed screen well completion technology, the gravel size is 2-4mm, after the installation of the well casing, fill the gap between the borehole and the well casing with gravels in a continuously and slowly way, make sure the gravel settled in place, when all the gravels calculated by the gap's volume were filled in, then seal the rest of the gap with clay balls of 4-6mm in diameter to the ground surface. The initial water level of the pumping well is 64.50m below the ground, and well discharge rate is 92m^3/h at 14.4m of drawdown, and the temperature of the geothermal water is 57℃.

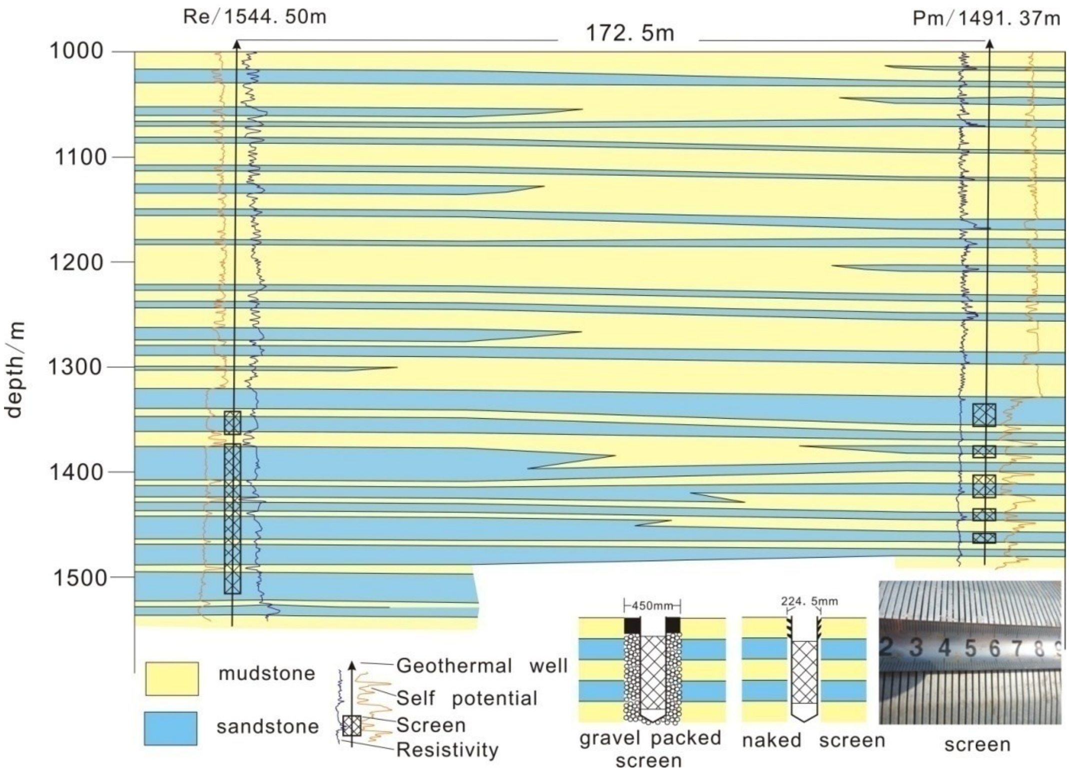


Figure 3 The cross section between the pumping and reinjection wells, well completion information

3.2 Spacing heating information

There are usually two kinds of spacing heating equipments been applied in China, one is the traditional radiator made of cast iron, which usually installed under the indoor windowsills[Figure4 (b)]. This kind of radiator needs a much higher temperature inflow fluid (hot water) of greater than 75℃[6], but for geothermal spacing heating projects, the inflow temperature of geothermal water greater than 45℃ has been tried and proved to be applicable. The other is floor radiator made of winded PVC pipes under the indoor floors[Figure4 (c)]. Lower temperature of 30℃-40℃ inflow fluid is needed for this kind of radiator. There are 14 buildings of 52,000m^2 using geothermal energy for winter heating in the project, the 1#-7#, 9#, 13#, 14# buildings is heated by traditional cast iron radiator, and the rest buildings are heated by PVC pipe floor radiator[Figure4 (a)].

The original geothermal water from pumping well is 56℃, which is cooled down to 42℃ at the first stage heat exchanger in Control room, providing thermal energy to heat up a circulation water to 54℃ to meet the energy needs of cast iron radiator. The tail geothermal water from the first stage heat exchanger is further directed into the second stage heat exchanger, where it is further cooled down to 30℃, providing thermal energy to heat up another circulation water to 40℃ to meet the energy needs of PVC floor radiator. The heat depleted tail water from the second stage heat exchanger is reinjected back into the geothermal reservoir.

1#-11# are residential buildings, 12#-14# are office buildings, red labelled buildings are heated by cast iron radiator, the white labelled buildings are heated by PVC floor radiator

(a) Layout of the project

(b) Cast iron radiator

(c) PVC floor radiator

Figure4 The wells location and heating equipment sketch map

4 SITE GEOLOGY

4.1 Stratigraphy

Unveiled by the well Re, the stratigraphy in the study area is as following:

(1) Quaternary (Q): The thickness of Quaternary is about 260m, parallel unconformity contact with Neogene Minghuazhen group. The upper part is made of yellowish brown clay, intercalated with fine sand or silty clay. And lower part has the same rock property as the upper part, except contains some layers of bluish grey and reddish brown clay.

(2) Neogene Minghuazhen group(Nm): The thickness of this strata is 890m, which is made of brownish yellow slightly diagenetic mudstone, interbedded with grayish white slightly diagenetic fine sandstone. The strata are conformity contact with underlying Neogene Guantao group.

(3) Neogene Guantao group(Ng): The thickness of this strata is 386m, unconformity contact with palaeogene Dongying group. The upper part is made of brownish yellow or brownish red median diagenetic mudstone, intercalated with grayish white median diagenetic fine sandstone. The lower part consist of thick layers of grayish white median diagenetic coarse sandstone and conglomerate sandstone, intercalated with brownish red median diagenetic mudstone. The sandstone shows a lower self potential value and higher resistivity value in the physical well logging, and mudstone shows a higher self potential value and lower resistivity value(figure3).

(4) Palaeogene Dongying group(Ed): The reinjection well drilled into the strata for 8.5m, which mainly contains near complete diagenetic mudstone of brownish red or grayish green.

4.2 Reservoir lithology

The two wells of the project exploit and reinjection into the lower part of Guantao group(Figure 3), there is a huge layer of mudstone at the burial depth of 1290m-1320m, insulating the lower part of Guantao group from the upper strata, so we can consider the lower part of the Guantao group as the geothermal reservoir, and the overlaid strata as reservoir's cap. According to the granular analysis results, the average particle diameter of the reservoir rock is about 0.5-2mm(table 1).

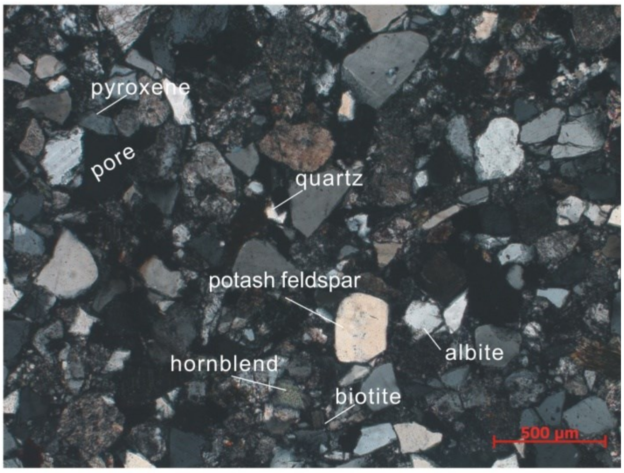
Observed under electronic microscope, the reservoir rock has a granular structure, it is consisted of rock fragments of chalcedony, and crystal fragments of quartz, potash feldspar , albite, pyroxene, biotite and hornblende. The pores between the grain particles have a various shape. The diameters of the pores range from 0.001mm to 0.05mm.

The rock identification result shows that the core section contains about 4% of chalcedony, 50% of quartz, 10% of potash feldspar, 17% of albite, 5% biotite, 3% of hornblend and 1% of pyroxene. With 5% of clay cementation and 3% of dark mineral. The rock's name is median sized granular feldspar sandstone (figure 5).

Table 1 The percentage of the particle size in core samples %

sample	Depth of the core sample/m	Particle size/ mm				
		2~5	0.5~2	0.25~0.5	0.075~0.25	<0.075
1	1404.00-1404.20	15.0	47.6	10.0	11.2	16.2
2	1420.00-1420.20	11.8	49.7	12.8	13.8	11.9
3	1436.00-1436.20	21.7	42.1	7.0	11.1	18.1
4	1440.00-1440.20	23.8	42.3	6.3	10.3	17.3
5	1456.00-1456.20	23.4	48.5	6.3	9.2	12.6
6	1476.00-1476.20	22.2	50.4	6.7	9.0	11.7
7	1490.00-1490.20	21.5	49.8	5.8	0.6	22.3
8	1508.00-1508.20	19.7	36.8	13.6	15.4	14.5
9	1520.00-1520.20	33.9	53.0	3.6	3.3	6.2
10	1530.00-1530.20	36.5	43.8	4.6	4.2	10.9


(a) Sampling



(b) Section under electronic microscope

Figure5 The core sampling, and identification under electronic microscope

4.3 Reservoir permeability

To evaluate the permeability of the geothermal reservoir, and check the connectivity between the two wells, we conducted an aquifer test by using the well Re as pumping well, and the well Pm as the water level drawdown monitoring well. The pumping rate was set at $75m^3/h$ and pumped for 14400 hours, the maximum drawdown in the well Re is 16.29 m, the maximum drawdown in the well Pm is 1.341 m. Theis analysis shows that the transmissivity of the geothermal reservoir is 950 m^2/d, and the storitivity of the reservoir is 2.82E-4, set the average reservoir thickness to 120m based on well Re and well Pm, the hydraulic conductivity of the reservoir is about 7.91m/d. The Theis recovery analysis calculated the transmissivity of the geothermal reservoir is 947 m^2/d, and the hydraulic conductivity of the reservoir is about 7.89m/d, which confirmed each other.

4.4 Water chemistry

The chemical component's concentrations of the geothermal water of the two wells are basically the same, the water type is Cl-Na, the percentage of molarity of Na is upto 91%, and the percentage of molarity of Cl is upto 78%, The total TDS is about 5g/l(table2).

able 2 The chemical component's concentration of geothermal water mg/l

Element	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	TDS
Re	13.07	1743	101.7	20.52	2157.6	654.61	229.06	4866.29
Pm	14.44	1732	102.4	20.43	2218.93	654.61	214.44	4880.95

5 PORJECT CONSTRUCTION AND OPERATION

5.1 Reinjection facilities

Pierre Ungemach had listed the 11 main factors that cause well and formation impairment by water injection into sandstone geothermal reservoir, which are (1) chemical incompatibility between injected and formation fluids; (2) microbiological effects; (3) water sensitivity of sandstones; (4)suspended solids; (5) fines migration within the injected formation; (6)trapped gases; (7) air contamination; (8) incompatible chemical additives and inhibitors; (9) thermodynamic changes induced by the injection process; (10) injection flow rates; (12) inadequate well completion[7]. LIU Xue-ling et al. conducted a blockage investigation related to the reinjection into sandstone geothermal reservoir, and draw a conclusion that the suspended fine particle accounts for 50% of the blockage, and reproduction of microbes accounts for 15% of the blockage, Chemical settlement accounts for 10% of the blockage, air bubble accounts for 10% of the blockage, clay swelling accounts for 5% of the blockage, an reservoir's particle rearrangement accounts for 5% of the blockage, the rest of the blockage caused by unidentified causes[8].

The project aims to inject the heat depleted geothermal tail water back into the geothermal reservoir, the chemical components in the tail water is nearly the same as that of the geothermal water in the reservoir itself, so the (1), (3),(8) problems listed by Pierre Ungemach are not exist.

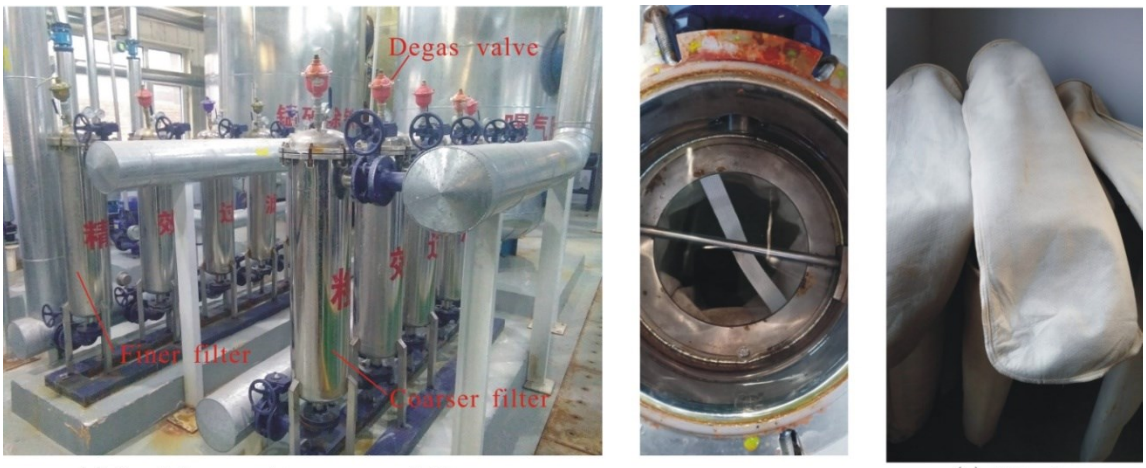
To avoid the clogging problems, under a thoroughly investigation of previous research results, the following measures were taken during the project construction.

5.1 .1 Using heat exchanger to shorten the circulation path avoiding air contamination

Since the geothermal water stays in a slightly reducing environment referred by the presences of Fe^{2+} ions , the air contamination can rapidly change the Fe^{2+} ions into Fe^{3+}based less soluble minerals, which is harmful for reinjection practice. There are two stages of heat exchanger been implemented at the project, in this practice, the geothermal water is used as heat source to provide thermal energy for the circulation fluid of the heating system, and the cooled geothermal water flows into the next steps of the reinjection system. That way the geothermal fluid circulation path is constrained in the control room and has very short flowing path, which avoids air from entering the geothermal water during heat extraction process.

5.1.2 Coarse and fine two stage filters to remove the suspending solids avoiding physical blockage

Previous researches have Pointed out that the suspending fine particles in the geothermal water are the main causes of reinjection clogging. The project adopted two kinds of suspend particles remove apparatus to deal with the fine particles in the geothermal water, which are Cyclone desander installed right before the heat exchangers to remove particle size greater than 0.1mm, and two groups of parallel arranged coarse and fine filters installed right after the heat exchangers to remove fine particles. There are five filters in each group(Figure 6(a)), each filter has a capacity to deal with 20 m^3/h of geothermal water, for it is parallel installed, one of the filter can be shortly shut down to cleanse the filter bag in case of blockage indicated by a large increase of pressure difference between the inlet and outlet of the filter(Figure 6(b),(c)). The coarse filter can remove the particles size greater than 50 μm, and the fine filter can remove the particles size greater than 5 μm that is less than most of the pore diameters in the reservoir.



(a) Parallel arranged two groups of filters (b) Inside of the filter (c) Filter bags

Figure 6 The configuration of coarse filters and fine filters

5.1.3 Gas deprive instrument to remove the separated gases avoiding gas blockage

There are usually dissolved gases in the geothermal water; it will separate from the geothermal water when temperature or pressure drops. The severity of the gas problem to the reinjection blockage depends on how much gas is entrained in the reinjection water, usually a large deair tank installed after the filters is needed to remove the gas. There is not a large amount of gas in the geothermal water for the project, we installed a degas valve at the top of each filter to remove the gases in the geothermal water(Figure 6(a)).

5.1.4 Thrust the injection pipe-end deep under well water's surface avoiding air entering

Thrusting the injection pipe-end under the water table of the Reinjection well rather than hanging it above the water table, which can serve two purposes. The one is avoiding air entering into the reinjection water that causes air clogging at the reservoir; the other is that the flowing of reinjection water can provide an additional reinjection pressure by its momentum.

5.1.5 Longer well screen to ensure sufficient injection space

The longer the well screen, the larger contact area between the reinjection section and reservoir is, and the easier the reinjected water enters into the reservoir. As for the project, the well Re has a screen length of 169.58m (Figure3),which penetrated through all the aquifer sections of the geothermal reservoir.

5.1.6 Large diameter borehole with gravel pack to provide a high permeable zone around the screen, while restraining the reservoir rock from collapsing near borehole

The Neogene sandstones and mudstones are usually slight to median diagenetic rocks(Figure 7(a)), which can weakly support the borehole from collapsing. Is case of well completion with naked screen as Pm , under the pumping circumstance, the fine particles of the fallen decomposed reservoir rocks would enter the well passing through the screen, and then be pumped out, leave the coarse particles piled up between the borehole and well casing, which will not block the geothermal water flow. But under the reinjection circumstance, the decomposed reservoir rock mass of mixed sand and clay will fill the gap between the borehole and the well casing, and lead to the permeability declination near well screen. Moreover it supplies large amount of fine particles into the reinjected water, and clogs the reservoir's pores. To avoiding this problem, the well Re was completed with gravel packed screen method, filling up the gap between the borehole and well casing with gravels(Figure 7(b)) , which can form a high permeable zone near the screen, and stop the reservoir's rock from decomposing.

(a) slighly diagenetic sandstone of reservoir core

(b) gravels been filled into the gap between borehole and screen

Figure 7 The sandstone cored at well Re and the gravels used for well completion

5.2 Reinjection operation

The project has been successfully operating for three years since its construction. The first year operated from 14/12/2016 to 17/03/2017, during the reinjection, 400 kg of ammonium molybdate($H_8MoN_2O_4$) and 5kg of Fluorescein Sodium as the tracers were add into the Well Re, the reinjection went pretty well after a few days of fluctuation , the steady reinjection rate was around 55m^3/h for the whole space heating season(Figure 8). But unfortunately, we did not detect the tracers at the pumping well (Pm) and at other observations wells 1-2km away from the well Re.

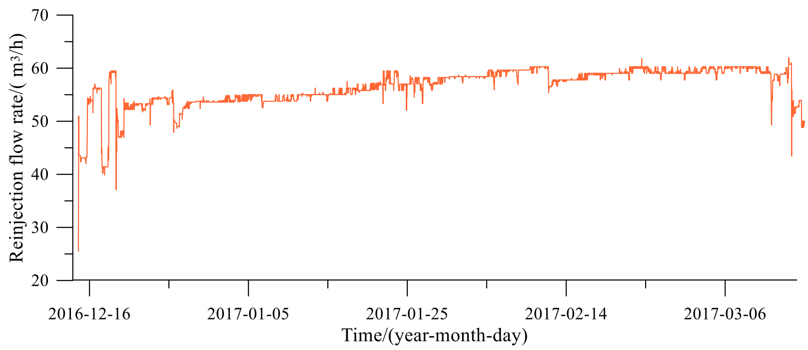


Figure8 The reinjection flow rate versus time curve for 2016-2017 heating season

The second year operated from22/11/2017 to 17/03/2018, the flow rate remained steady at around 60m^3/h during the period of 22/11/2017 to27/01/2018, and the reinjection flow rate was adjusted to about 50 m^3/h during the period of 28/01/2018 to 17/03/2018 during the reinjection. We used 400kg of copper sulfate ($CuSO_4$) as tracer injected into well Re before injection, but no tracer returned from well Pm during the whole season, the tracers put the year before did not be detected as well.

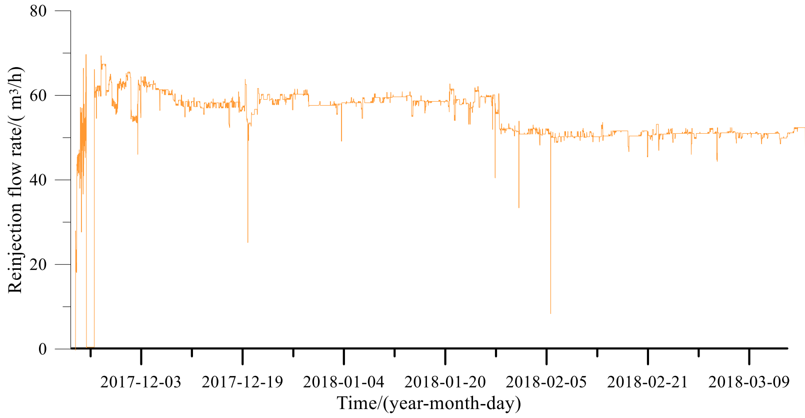


Figure 9 The reinjection flow rate versus time curve for 2017-2018 heating season

The third year started from 16/11/2018 to 25/03/2019, the reinjection flow rate was around 62m^3/h during the heating season, there were some large fluctuations due to pumping rate adjustment (Figure 10). During the reinjection process, we continued to check the pumping well for the tracers previously put into the well Re, still no tracer return was founded.

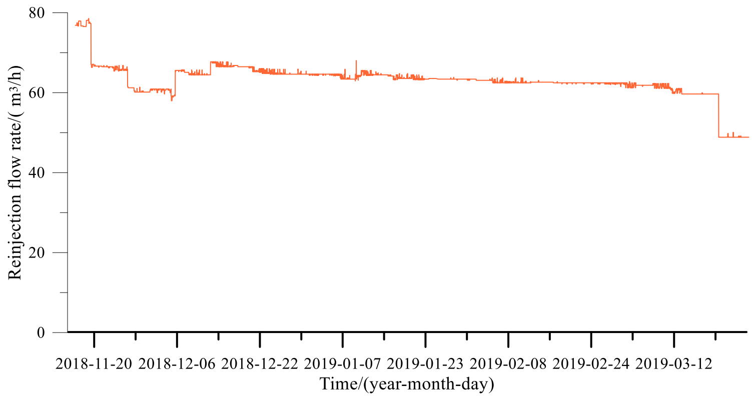


Figure 10 The reinjection flow rate versus time curve for 2018-2019 heating season

5.3 Temperature changes

The temperature of the geothermal tail water is about 26℃ lower than that of the geothermal reservoir, with massive reinjection, there sure posed a temperature cooling down threat for the geothermal reservoir. We conducted a continuous temperature monitoring at the outlet of well Pm during the reinjection operation, and observed a small scale of temperature fluctuation during each heating season may caused by the pumping rate fluctuation and air temperature fluctuation. But there is a slightly temperature drop year on year, during the heating season of 2016-2017, the average temperature of the well Pm outlet is 55.8℃, and in the heating season of 2017-2018, the average temperature of the well Pm outlet is 55.4℃; the average temperature of the well Pm outlet is 54.4℃ at 2018-2019 heating season.

6 CONCLUSION

Reinjection of heat depleted geothermal tail water in sandstone geothermal reservoir is feasible through a comprehensive measures to avoiding air contamination, entrained fine particles removing, separated gas removing. Longer well screen and large diameter borehole with gravel packed screen well completion method is a good practice for slightly to median diagenetic sandstone geothermal reservoir. More concerns should be put into the proper distance between the reinjection well and pumping well to avoid a premature thermal breakthrough at the pumping well.

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