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Long term reinjection practices in the Dezhou sandstone geothermal reservoir of North China Basin

ZHAO Jichu[1], BAI Tong[1], ZHANG Pingping[1], KANG Fengxin[2,3,4]*

1.Shandong Provincial Research Center of Geothermal Resources and Reinjection, Dezhou, 253072

2. College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China

3. 801 Institute of Hydrogeology and Engineering Geology, Shandong Provincial Bureau of Geology and Mineral Resources, Jinan 250014, China

4. School of Water Conservancy and Environment, University of Jinan, Jinan 250022, China

*Corresponding author: Kang Fengxin, kangfengxin@126.com

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ABSTRACT

Low-medium temperature water type geothermal resource is suitable to provide heat energy for residential seasonal heating needs, and reinjection of the cooled chemical composition no- changed geothermal tail water back into the geothermal reservoir is a necessary procedure to maintain the sustainable utilization and to prevent environmental pollution. But the reinjection in sandstone geothermal reservoir is a delicate project. The paper summarized the general performance of the demonstration reinjection project in sandstone geothermal reservoir at Dezhou city which operated continuous since 2016. Up to now, the project maintained a 6 consecutive years of nearly 100% reinjection rate. The distance between the production well and the reinjection well is 172.5m, the temperature of the geothermal tail water is around 35℃, and the temperature of geothermal water at the pumping outlet of the production well is around 55℃, the average production and reinjection rate is about 60m^3/h to accommodate the heating needs of 57 000 m^2 of residential buildings . There some slightly temperature fluctuations of the geothermal water observed at the pumping outlet of the production well, but without a stable downward trend, which suggested no thermal breakthrough occurs. The tracer test of Molybdenum ammonium acid shows a suspicious tracer travel time span of 320 days with a slight rise of Molybdenum ion concentration at the production well. The temperature loggings in the reinjection well showed slight temperature rise during off heating season, which suggested there is a weak heat replenish from ambient surround rock mass. The successful reinjection practices in the demonstration project draw a conclusion that long term reinjection in the sandstone geothermal reservoir is viable.

INTRODUCTION

Geothermal is a well known green energy, which is an environment friendly energy source for replacing coal to provide thermal energy for house heating in winter. Geothermal energy is widely adopted to provide heat resources for district heating in winter season in the northern China plain, there are about 3 000 geothermal wells been built to accommodate around 150 million m^2 of district heating needs. The usage of the geothermal energy contributed tremendously to the reduction of coal consumption of about 3 million tons annually. Northern Shandong plain is the main part of Northern China plain, the usage of geothermal energy in district heating started in 1998 at Dezhou city, which peaked at 2016 with about 1 200 geothermal wells to provide district heating for 60 million m^2 of residential buildings, 80% of the geothermal wells were built in the sandstone geothermal reservoir of Neogene Guantao group. Due to the low injecticity at sandstone geothermal reservoir, before 2016, the usage of geothermal water employed a “pumping-heat exchange-discharge” model, which posed some severe environmental threats such as chemical pollution of high salt content geothermal water, and fast pressure drawdown at geothermal reservoir. The demonstration reinjection project was constructed in 2016 at the very location of the first geothermal well to provide district heating in Shandong province, which adopted a “pumping-heat exchange-reinjection” model, and has experienced 6 consecutive years of nearly 100% reinjection of heat depleted geothermal water. The average pumping and reinjection rate is about 60m^3/h to accommodate the heating needs of 57 000 m^2 of residential buildings. Based on the success experience of the demonstration project, a governmental regulation issued in 2018 to require geothermal utilization enterprises to implement reinjection during providing seasonal heating service in Shandong province, the mandatory reinjection rate set to no less than 80% for sandstone geothermal reservoir and 90% for karst geothermal reservoir, who did not fit to the requirement, would be shut down. The implementation of the regulation has kicked a great number of geothermal heating company out of business. The paper summarized the performances of the demonstration project for the purpose of promoting geothermal utilization.

1 GEOLOGY BACKGROUND OF THE PROJECT

The project locates at the western edge of the Dezhou depression(Fig.1 up right), which is the northeastern part of Linqing depression, southeastern Baohai bay basin (Fig.1 left). Baohai bay basin is a Mesozoic-Cenozoic sedimentary basin(Li *et al*, 2010) , with the characteristics of fault depression in paleogene era and subsidence depression in Neogene-quaternary era(Jiang *et al*, 2014).

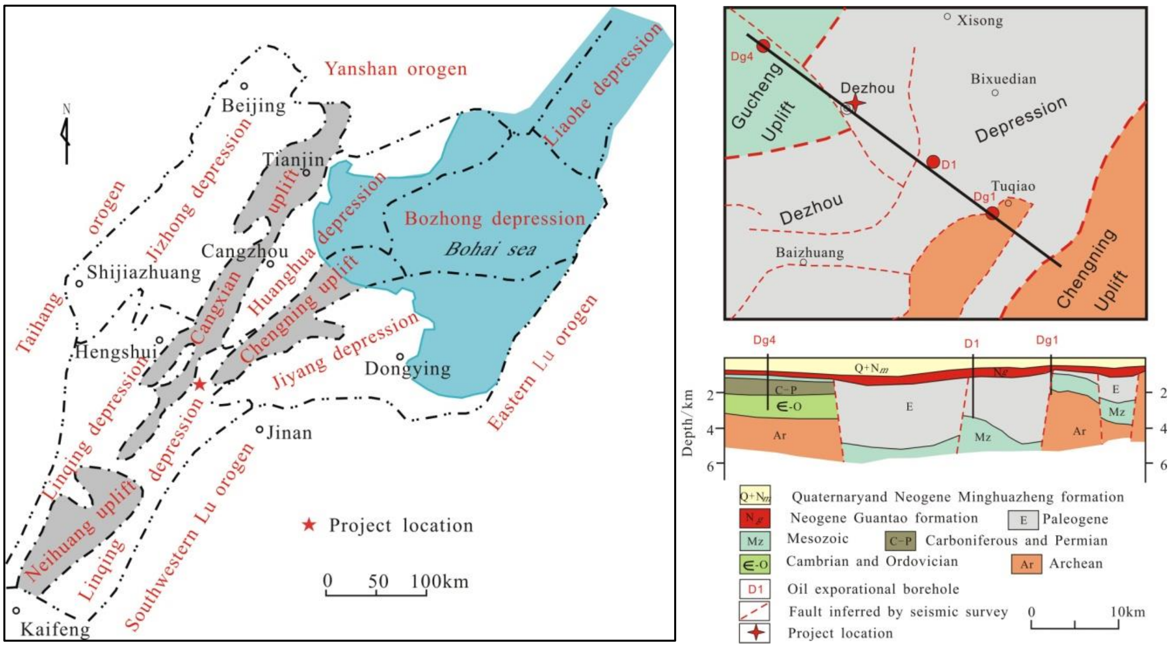

Figure. 1 Geological background of the project

The regional strata from bottom to top are (Fig.1 low right): (1) Archean metamorphic strata of granito-gneiss forming the crystal basement of the entire region; (2)Cambrian-Ordovician carbonate strata absent in the Chengning uplift area, and evenly distributed in the Dezhou depression and Gucheng uplift area with a total thickness of 1 200m; (3)Carboniferous-Permian clastic strata is about 800m thick, which has the same spacial distribution pattern with the Cambrian-Ordovician strata; (4)Mesozoic strata clastic strata 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. (5)Paleogene clastic strata absent in the Chengning uplift and Gucheng uplift area, At the eastern part of Dezhou depression, the thickness is about 150m revealed by borehole Dg1 at the uplifted area, and is about 2 000-4 000m in the depressed area.(6) Neogene Guantao 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 is 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 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 fine sand aquifers has a total dissolved solids less than 1g/l, which is mainly used for industrial agriculture and tap water supple(Zhao *et al*, 2021).

2 LAYOUT OF THE PROJECT

The project has one production well and one reinjection well, the distance between the two wells is 172.5m. The borehole depth of the production well is 1491.37m, with naked screen well completion technology; the total length of the screen assembly is 72.32m. The borehole depth of the reinjection well is 1544.50m, with gravel packed screen well completion technology; the total length of the screen assembly is 169.58m (Tab.1). Interpreted from the spontaneous potential logging data, there is an obvious thickness difference of the sandstone layers of the geothermal reservoir between the production well and reinjection well(Fig.2).

Tab.1 Information of the production well and reinjection well

Items	Production well	Reinjection well
Well completion date	1997.3	2016.8
Borehole depth/Well depth	1491.37m/1479.72m	1544.50m/1536.44m
Borehole diameter	Depth:0-109.80m, Φ=450mm Depth:109.80-212.66m, Φ=311mm Depth:212.66-1491.37 m, Φ=244.5mm	Depth: 0-281.33m,Φ=610mm Depth: 281.33-1544.50m, Φ=450mm
Well casing diameter	Depth:0-104.92m, Φ339×8.94mm， Depth:104.92-1479.72m,Φ177.8×9.19mm	Depth:0-281.33m, Φ339.7×9.65mm Depth:281.33-1536.44m,Φ177.8×8.05mm
Water seal method	Rubber bands, 1320.87m	Gravel pack at 1310.00-1544.50m; clay water seal at 0-1310.00m
Pumping rate/ drawdown/temperature	100.37 m^3/h/16.40m/55.5℃	92.24m^3/h/14.38m/57℃
Screen position	1335.6-1356.32m, 1376.29-1386.40m, 1396.55-1417.03m, 1428.28～1438.87, 1457.14～1467.56;Total length:72.32m	1343.4-1354.64m, 1366.40～1524.74m; Total length: 169.58m

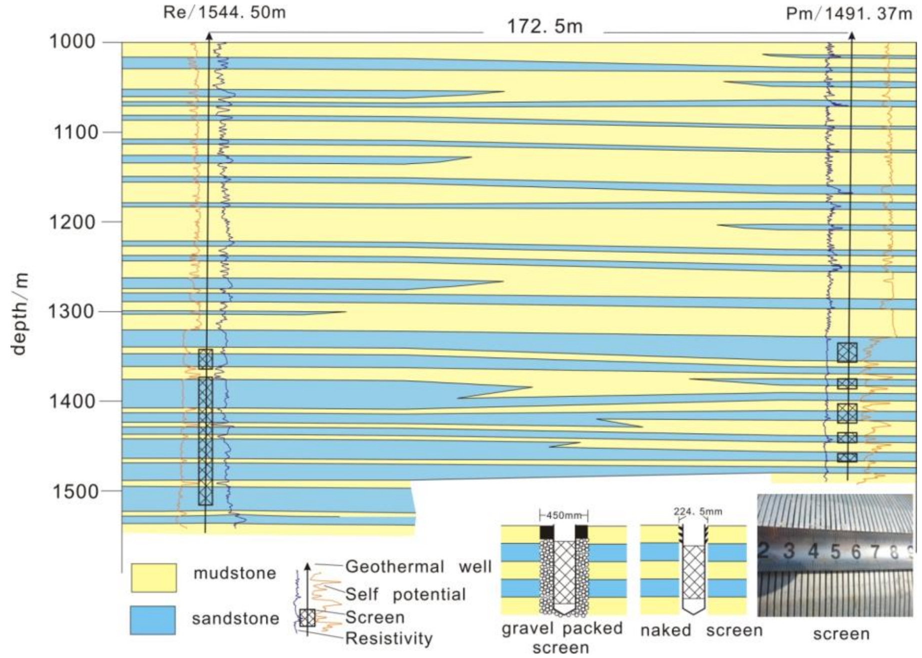

Figure. 2 The cross-section of productioin well and reinjection well

3 PERFORMANCE OF THE PROJECT

3.1 Pumping test

In order to determine the connectivity between the production well and reinjection well, as well as the hydrogeological parameters of the geothermal reservoir, we have performed two pumping test before and after the 2016-2017 heating season.

3.1.1 Pumping test before the 2016-2017 heating season

3.1.1.1 Data of pumping test

the pumping test was conducted during November 1th to November 15th, 2016. Pumping was conducted at the reinjection well, and the duration of the pumping is 14400 minutes, there are some fluctuations in the pumping rate during the early period of the test, but the deviations is les s than 5%, which complied with the criteria of pumping test (Wang *et al*, 2012), the average pumping rate is 76.3m^3/h(fig.3)。

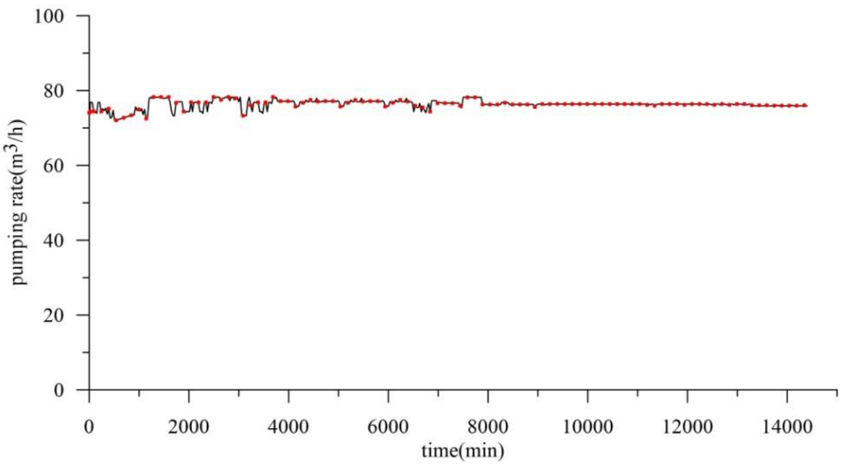

Figure. 3 Pumping rate versus time plot

The water level observed at the production well (used as an observation well) shows that the initial burial depth of the water level is 61.52m, the largest burial depth of the water level is 62.86m at the end of the pumping, with a maximum drawdown of 1.34m. There is a drawdown anomaly observed between the time span of 2310-2610minutes, the water level actually rose about 0.006m instead of drawdown. The water level rose above the initial water level after 32 minutes from the stop pumping, and the highest water level is 2.36m above the initial water level during 17490-17670 minutes of the test. There is an instant abrupt water level rising of 0.66m at the observation well at the stop pumping, and then the water level underwent a rapid recovery rate during the first 720 minutes after stop pumping, followed by a slower recovery till reach the highest point, and then slowly fall down afterward(Fig.4).

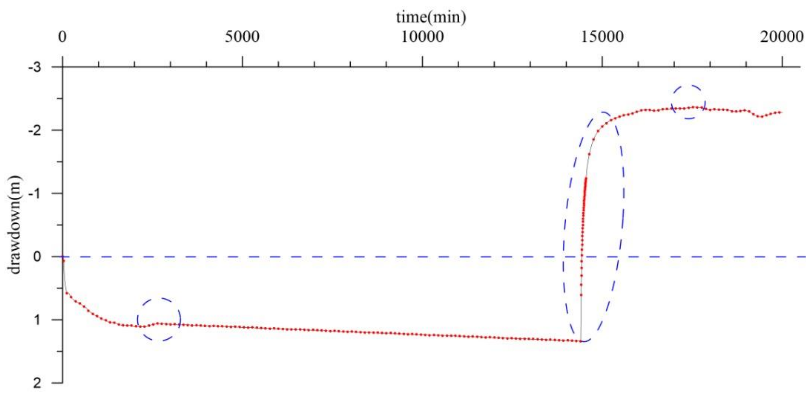

Figure. 4 The water level drawdown versus time curve

3.1.1.2 Observation data analysis

Informed from the reaction of water level changes in the observation well, the pumping in the production well has caused an obvious water level drawdown in the observation well, which indicated a good connectivity between the two wells. The rising of water level above the initial water level after the pumping suggest that there may have an upward temperature change trend in the observation well along with the progressing of pumping during pumping test, which lightened the density of water in the observation well cylinder and caused the water level to rise. The water level drawdown anomaly also indicated there is a density lightening in the observation well with the progressing of pumping, during the pumping time span of 2310-2610 minutes, the density lightening effect exceeded the pumping drawdown effect, and thus appeared as the water level rising anomaly. The water level drawdown caused by pumping is compensated by the lightening of water density in the observation well cylinder, which caused the water level drawdown appeared less severe than they actually are, thus, in order to gain a relatively correct hydrogeology parameters from the observation data, using the early stage of drawdown data is more appropriate than using the drawdown data of later stage. The instant abrupt rising of water level at the stop pumping may result from a phenomenon of "Water hammer effect". The slowly water level falling down at the end of recovery observation period may caused by the slowly cooling of water temperature in the observation well cylinder.

3.1.1.3 Parameters calculation

(1) Theis curve match method

To estimate the hydrogeology parameters, we assume the geothermal reservoir is homogeneous with infinite boundaries, and complied with the Theis assumption. Theis formula is as follow (XUE, 1997):

$$s = \frac{Q}{4\pi T} W(\mu)$$

$$\mu = \frac{r^2}{4at}$$

where s is the water level drawdown in the observation well (m); Q is the pumping rate (m^3/d); W(μ) is a well function, its value can be calculated from a given variable μ ; r is the distance between the pumping well and the observation well (m); a is the piezometric conductivity of the geothermal reservoir (m^2/d), which has the value of T / u^*; u^* is the storativity of the geothermal reservoir; T is the transmissivity of geothermal reservoir(m^2/d). t is the drawdown observation time from the start pumping (d).

The functions above can be translated into the form as follow:

$$\log s = \log W(\mu) + \log \frac{Q}{4\pi T}$$

$$\log t = \log \frac{1}{\mu} + \log \frac{r^2}{4a}$$

Assume the Q, T, a, r are constants for a designed pumping test, then the s-t observation data points plot is in the shape of W(μ)-$\frac{1}{\mu}$ plot curve with an offset of ($\log\frac{Q}{4\pi T}$, $\log\frac{r^2}{4a}$) , we can match s-t observation data points with the standard curve of W(μ)-$\frac{1}{\mu}$ to estimate the parameters of u^*,T of the geothermal reservoir.

Understood from the observation data analysis discussion, we used the first stage of s-t data plot to match up the standard curve of W(μ)-$\frac{1}{\mu}$ (Fig.5).

Read from the Fig.4, when W(μ) = 1, the drawdown (s) is 0.53m, then

T= 76.3*24/(4*3.1416*0.53)=275m^2/d

When t=90 minute, the $\frac{1}{\mu}$ is 3, then

a = 172.5*172.5*24*60*3/(4*90)= 357075 m^2/d; then

u*=T/a=275/357075=7.70E-4

So the storativity of the geothermal reservoir is 7.70E-4, and the transmissivity of geothermal reservoir is 275 m^2/d, the parameters is agree with the regional empirical values.

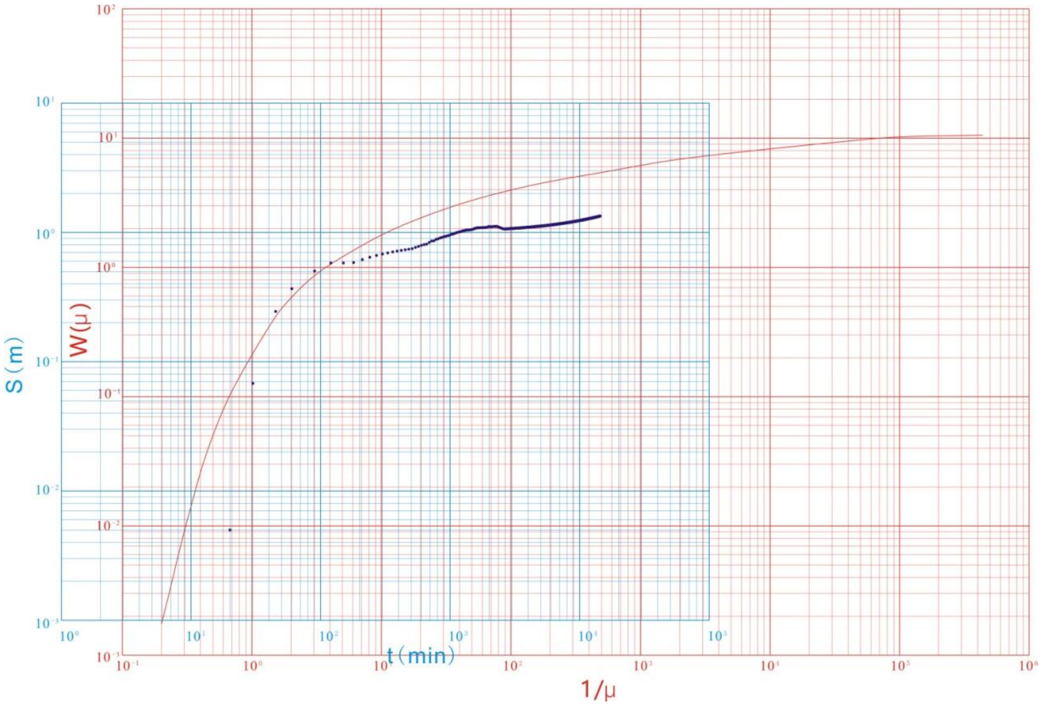

Figure. 5 The match between s-t data plot and standard curve of W(μ)- $\frac{1}{\mu}$

(2) Theis recovery method

After the pumping shut down, the residual water level drawdown at the observation well can be calculated from the formula bellow:

$$s' = \frac{2.3Q}{4\pi T} \log\left(\frac{t}{t'}\right)$$

Where S' is the residual water level drawdown at the observation well (m); t is the elapsed time from the start of the pumping (minute); t' is the elapsed time from the ending of the pumping (minute);

In order to eliminate the temperature effect to the residual water level drawdown, we used the highest water level in the recovery period as the static water level, then Plot the s' and t/t' in a semi log coordinate system as follow (Fig.6):

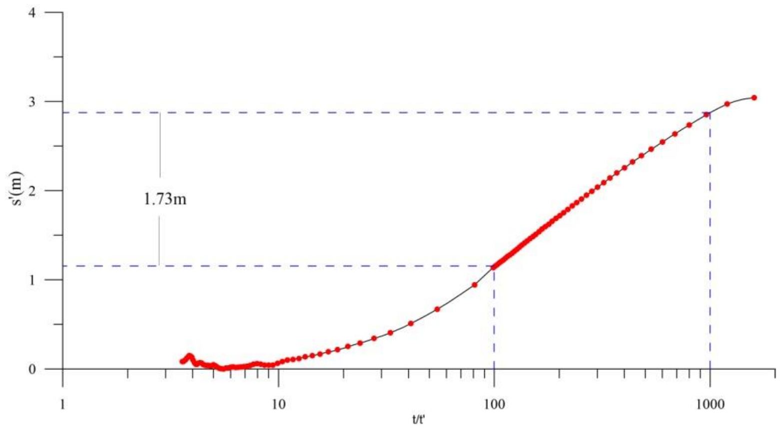

Figure. 6 S' versus t/t' plot of observation well

As discussed above, the late period of waterlevel recovery is affected by the cooling of water temperature in the observation well cylinder, we used the early stage of water level recovery data to calculate the transmissivity of the geothermal reservoir, reading from fig.5, the slop of the s'-t/t' plot is about 1.73 at the early period, thus:

$T = \frac{2.3*76.3*24}{4*3.1416*1.73} \approx 194\ m^2/d$

The calculated value of T has the same order of magnitude with that obtained from the Theis curve match approach, which is 275 m^2/d.

3.1.2 Pumping test after the 2016-2017 heating season

The water level observation data at the previous pumping test indicated an unwanted water level changes caused by temperature effect of density lightening in the observation well cylinder along with the progressing of pumping, resulted in a severe deviation between s-t plot and Theis standard curve. To address this problem, another pumping test was conducted after the 2016-2017 heating season.

3.1.2.1 Data of pumping test

the pumping test was conducted during May 3th to May 18th, 2017. Pumping was conducted at the reinjection well, and the duration of the pumping is 14380 minutes, there are some fluctuations in the pumping rate during the early period of the test, but the deviations is less than 5%, which complied with the criteria of pumping test, the average pumping rate is $73.9m^3/h$(Fig.7)。

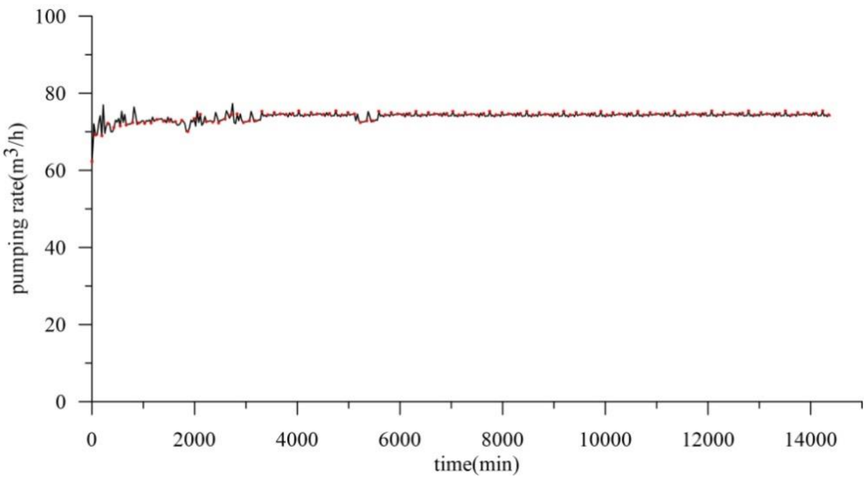

Figure. 7 Pumping rate versus time plot

To understand the temperature variation in the pumping well and observation well, temperature measurements were taken in the pumping and observation well by combine a thermometer with the piezometer downhole. The pumping test is conducted 30 days after the long term exploitation of geothermal water for space heating, and the reinjection water temperature averages 35℃ in the 4 month long heating season, followed by an about 1 month of extend reinjection period of geothermal water of 54 ℃directly pumped from the production well to fulfill the needs of tracer test. The pumping is carry out at the reinjection well during the test, and the temperature of the pumping well is around 44℃ during the pumping period, which is about 10℃ below the reservoir temperature, and indicated the reservoir adjacent to the reinjection well is cooled 10℃ by the reinjection. There is about 2 ℃ temperature jump at the pumping stop, then the temperature gradually cool down(Fig.8) . The production well is used as the observation well for the pumping test; water temperature keeps a slow cooling pace during the whole test period with a total temperature drop less than 5℃.

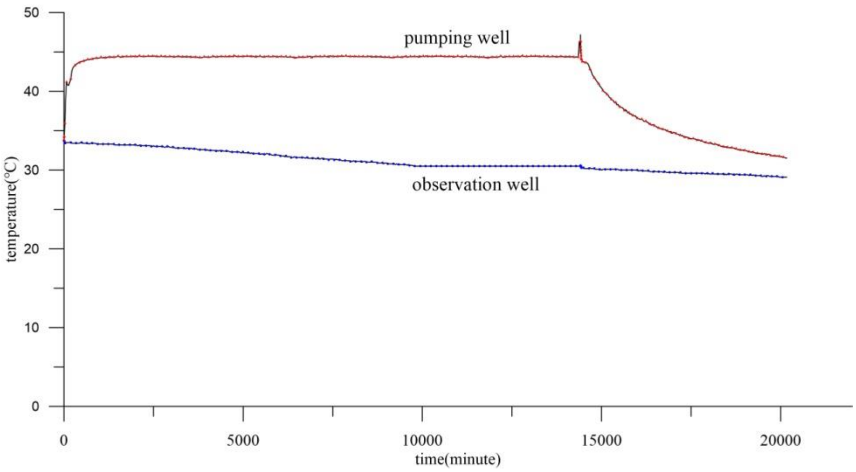

Figure. 8 Temperature versus time plot at the pumping and observation well

The initial burial depth of the water level is 76.86m at the observation well, which is 15.34m deeper than that before the heating season. The water level difference between the start and end of the heating season indicates that the reinjection of the demonstration project could replenish only a small portion of geothermal water been withdrawn regionally, There may still has a regional water level recovery trend in both pumping and observation well during the pumping test as a result of replenish from porous flow from the geothermal reservoir afar.

The drawdown versus time plot appear some small fluctuations during the first 6000 minutes of the test, compared with the pumping rate versus time plot , the fluctuation is caused by the variation in pumping rate. The plot curve appears smooth at the late time of the test, and the maximum drawdown is 1.32m(Fig.9). During the recovery period of the test, as with the water level observation of the previous test, there is about 0.3m of instant water level jump at the stop pumping, then a rapid recovery rate followed by a slower recovery rate. The water level falling down at the end of the test is caused by the cooling of water in the well cylinder.

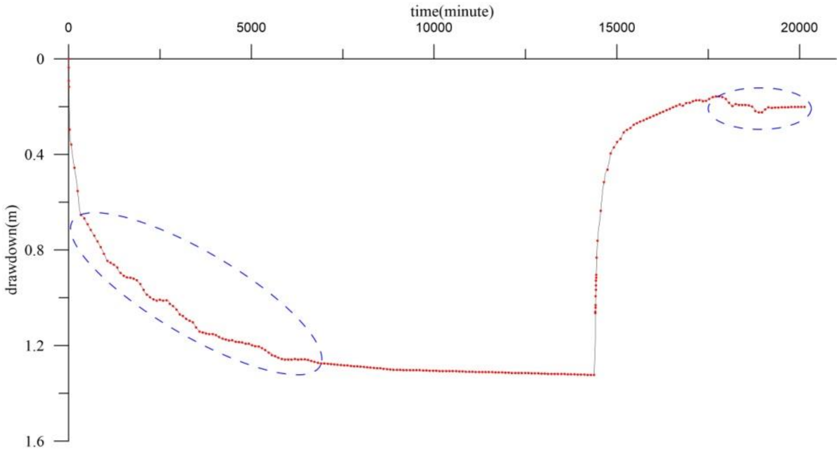

Figure. 9 the water level drawdown versus time curve

3.1.2.2 Parameters calculation

(1) Theis curve match method

The S-t plot matches the Theis standard curve well(Fig.9), read from the Fig.10, when W(μ) = 5, the drawdown (s) is 0.90m, then

T= 73.9*24*5/(4*3.1416*0.9)=784m^2/d

When t=3000 minute, the $\frac{1}{\mu}$ is 800, then

a = 172.5*172.5*24*60*800/(4*3000)= 2856600 m^2/d; then

u*=T/a=784/2856600=2.74E-4

So the storativity of the geothermal reservoir is 2.74E-4, and the transmissivity of geothermal reservoir is 784 m^2/d, the parameters have the same order of magnitude with that calculated previously, but as discussed above, due a regional recharge from the geothermal reservoir afar, the transmissivity calculated may higher than that actually is, and the storitivity is lower than that actually is.

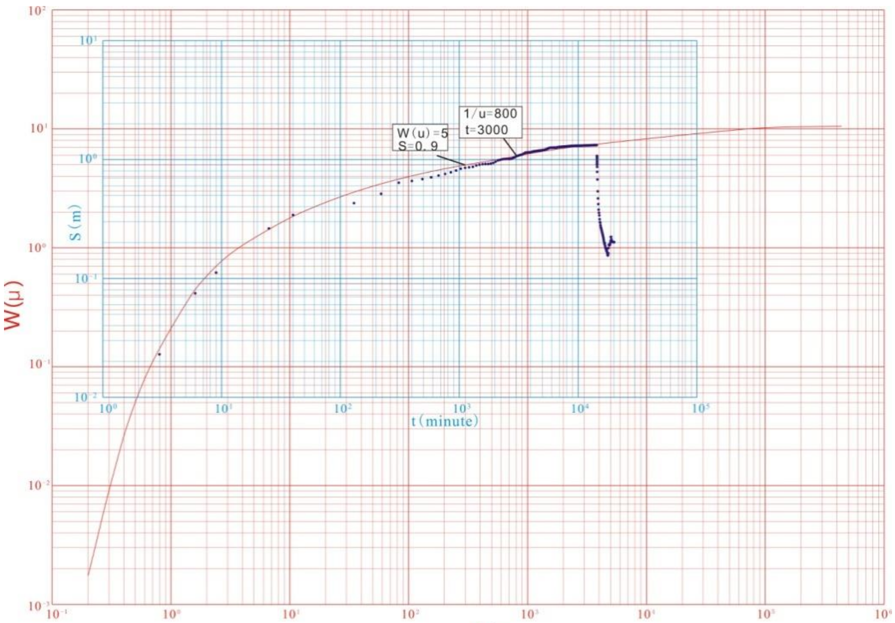

Figure. 10 The match between s-t data plot and standard curve of W(μ)- $\frac{1}{\mu}$

(2) Theis recovery method

Using the same strategy as previous, we use the early period of recovery data to calculate the transmissivity of the geothermal reservoir(Fig.11), the result as follow:

$$T = \frac{2.3*73.9*24}{4*3.1416*0.52} * (\log 230 - \log 26) \approx 591 \text{ m}^2/\text{d}$$

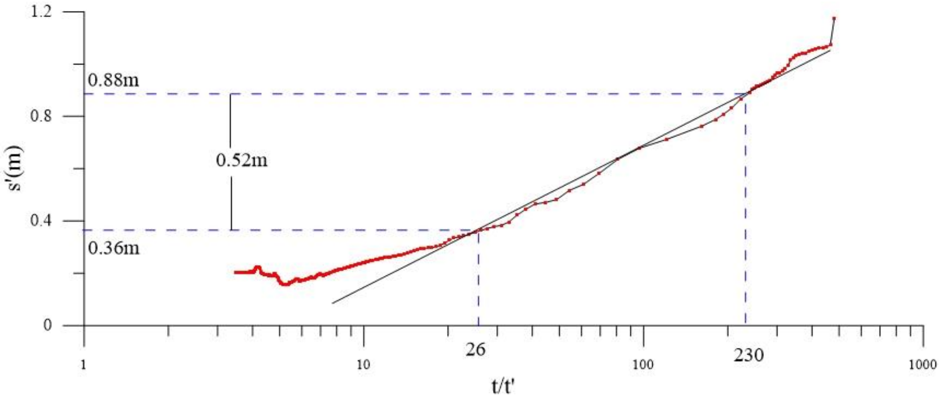

Figure.11 S' versus t/t' plot of observation well

The calculated value of T has the same order of magnitude with that obtained from the Theis curve match approach, which is 784 m^2/d.

3.2 Reinjection

The demonstration project has successfully conducted 6 consecutive heating seasons of reinjection since its construction, except for the 2016-2017 heating season when a 0.4-0.6 Mpa reinjection press was applied at the reinjection well head, in the rest of 5 heating seasons, the water level is below the well head during reinjection to sustain a nearly 100% reinjection ratio of tail geothermal water, the total amount of the reinjected geothermal tail water is 1 129 200 m^3.

3.2.1 Reinjection in 2016-2017 heating season

The demonstration project started to trial reinjection at November 25th, 2016, 10am, not sure about the reinjecticity of geothermal reservoir, the reinjection rate was controlled manually, the average reinjection rate is controlled around 20m^3/h, the initial water level bury depth is 68.70m, water level rose to the well head after 2580 minutes of reinjection at the time of Nov. 27th 2016, 5am, then cease the reinjection. The second trial reinjection started at Nov. 27th 2016, 14:30, the reinjection rate was set to 20 m^3/h, and stopped at Nov. 28th 2016, 8:00 due to the overflow at the reinjection well. The third trial reinjection started at Nov. 28th 2016, 14:30, with the same reinjection rate, overflow occurred at Nov. 29th 2016, 7am. After the three trial reinjection without a promising result, we assumed there may have some blockages in the reinjection well, then a back washing of 60 m^3/h from Nov. 30th 2016, 11am to Dec. 3th 2016, 10am. The fourth trial reinjection started at Dec. 3th 2016, 17:30, the reinjection rate set to 30 m^3/h, and water level rose to the well head at Dec. 5th 2016, 12:30, keep the water level just below the well head, and continue reinjection to Dec. 8th 2016,9:30, and the reinjection rate of 30 m^3/h was sustained. At Dec. 8th 2016,10am, a pressure about 0.56Mpa was applied to the reinjection well, and a reinjection rate sustained at around 60 m^3/h to Dec. 14th 2016,8am, which proved a sustainable high reinjection rate can be reached through pressurized reinjection. From Dec. 14th 2016,9 am to 2 pm, 800 kg of 7-Molybdenum ammonium acid [$(NH_4)_6Mo_7O_{24}$] and 5 kg of fluorescein sodium ($C_{20}H_{10}Na_2O_5$) as tracers been added to the reinjection well.

At Dec. 14th 2016, 16:30:00, the project started to run practically, the temperature of tail geothermal water from the spacing heat outlets of the floor radiator is around 35℃, there are some fluctuations at the early period the reinjection, with a reinjection pressure controlled at around 0.44Mpa at the reinjection well head, and the reinjection rate show a relative large variation between 40 m^3/h to 60 m^3/h. after the initial period of time, instead of controlling the reinjection pressure, the returned geothermal tail water was fully reinjected back into the geothermal reservoir, there is an abrupt pressure rose from 0.44Mpa to 0.51Mpa at Dec. 21th 2016, the highest reinjection pressure is 0.576Mpa observed at 2016/12/27 21:30 during the heating season, then the pressure started to fall down gradually and remained around 0.50Mpa afterward, the reinjection rate was determined by the geothermal water needed for spacing heating, which is around 56 m^3/h, the maximum reinjection rate was about 60 m^3/h during the whole heating season. The official heating season ends at March 15th in the study area, but without recovery of the tracers from the pumping well, we extended the heating with a lower pumping rate to 2017/3/31, 14:00. then a reinjection of unused geothermal water directly withdrawn from the production well with temperature around 54℃ till 2017/4/29 5:00(Fig.12). The total reinjected geothermal tail water is about 167 600 m^3 in 2016-2017 heating season.

3.2.2 Reinjection in 2017-2018 heating season

Due to malfunction of the pump in the production well, the project started to provide heating service at November 22th 2017 for the 2017-2018 heating season. The reinjection rate is determined by the geothermal water for spacing heating needs, which can be divided into 2 stages roughly, the reinjection rate is about 60 m^3/h at the first stage from November 22th 2017 to January 28th 2018, and about 50 m^3/h at the second stage from January 28th 2018 to March 17th 2018 . The average temperature of the reinjection geothermal tail water is around 34℃.The initial water level bury depth at the reinjection well was 64.79m, and the water level at the reinjection well was under the ground surface in the whole heating season, no additional pressure was needed to sustain the reinjection(Fig.13). The total reinjected geothermal tail water is about 151 400 m^3 in 2017-2018 heating season.

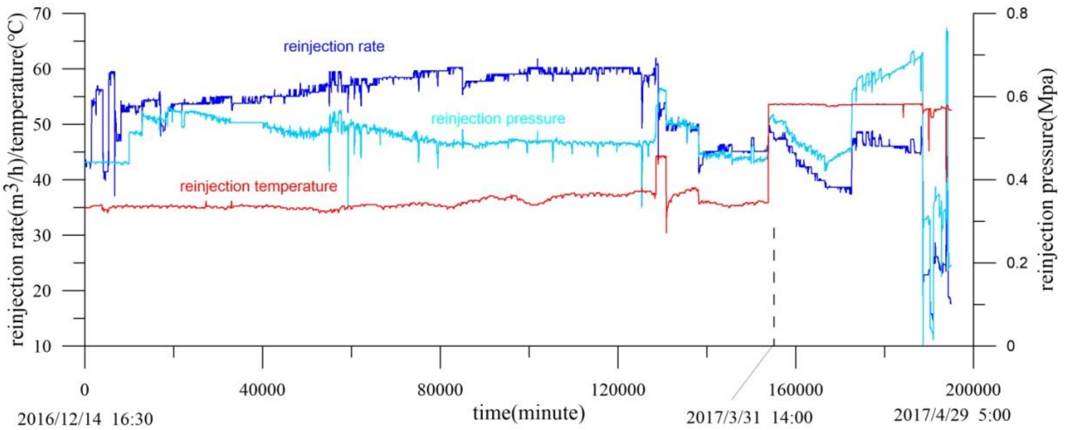

Figure. 12 The reinjection temperature, reinjection rate and reinjection pressure at 2016-2017

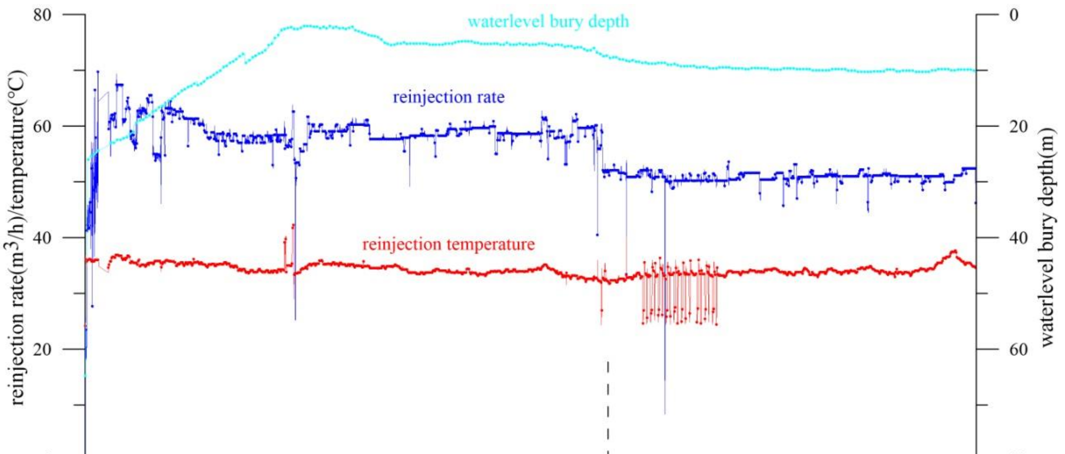

Figure. 13 The reinjection temperature, reinjection rate and reinjection pressure at 2017-2018

3.2.3 Reinjection in 2018-2019 heating season

The project started to provide heating service at November 15th 2018 for the 2018-2019 heating season. The pumping rate (then the reinjection rate) was controlled by the room temperature via a frequency conversion pump. Due to the large difference of temperature between daytime and that of night time at the early stage of the heating season, the reinjection rate curve appeared as large oscillation zigzag shape, the average reinjection rate is about 65 m^3/h. The oscillation altitude of the reinjection rate curve calmed down at the later stage of the heating season, and the average reinjection rate is about 60 m^3/h. The temperature of the reinjected geothermal tail water is around 35℃. The initial water level bury depth at the reinjection well was 71.80m , and the average bury depth of the water level in the reinjection well was 59.93m, the minimum bury depth was 48.48m for the whole heating season, no extra pressure was need to maintain the reinjection(Fig.14). The total reinjected geothermal tail water is about 194 800 m^3 in 2018-2019 heating season.

3.2.4 Reinjection in 2019-2020 heating season

The project started to provide heating service at November 9th 2019 for the 2019-2020 heating season. The pumping rate (then the reinjection rate) was adjusted manually according to the weather via a frequency conversion pump. The average reinjection rate is about 34 m^3/h from 2019/11/9 to 2019/11/12, about 48 m^3/h from 2019/11/12 to 2019/11/19, about 57 m^3/h from 2019/11/19 to 2019/12/2, about 54 m^3/h from 2019/12/2 to 2019/12/5, and about 48 m^3/h from 2020/3/24 to 2020/4/2. The average reinjection rate is around 65 m^3/h in the majority time of the heating season from 2019/12/5 to 2020/3/24.

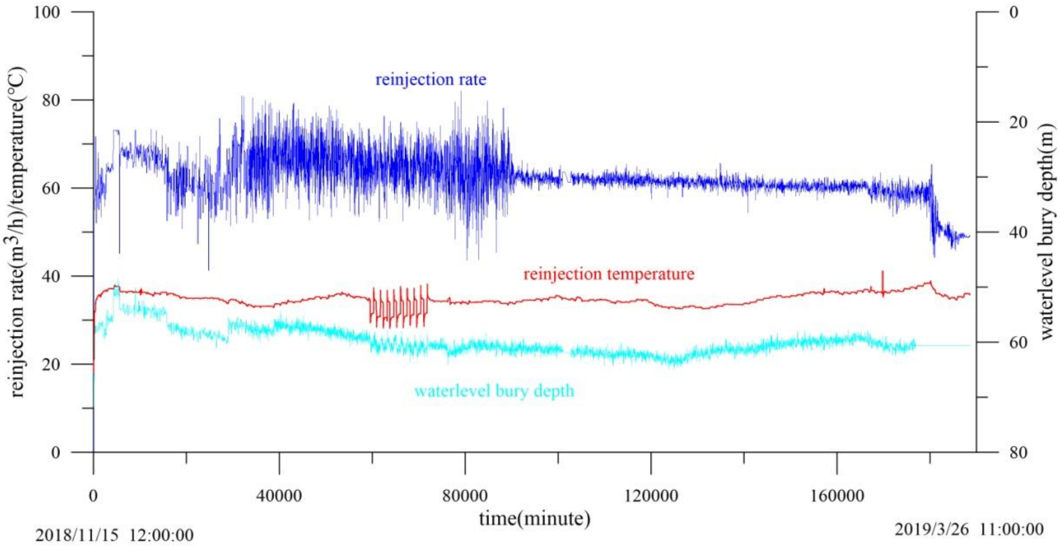

Figure. 14 the reinjection temperature, reinjection rate and reinjection pressure at 2018-2019

.The temperature of the reinjected geothermal tail water is around 35℃. The initial water level bury depth at the reinjection well was 77.65m , the water level in the reinjection well rose gradually at the early stage of the reinjection, then remain near constant at a bury depth of 22m, no extra pressure was need to maintain the reinjection(Fig.15). The total reinjected geothermal tail water is about 206 100 m^3 in 2019-2020 heating season.

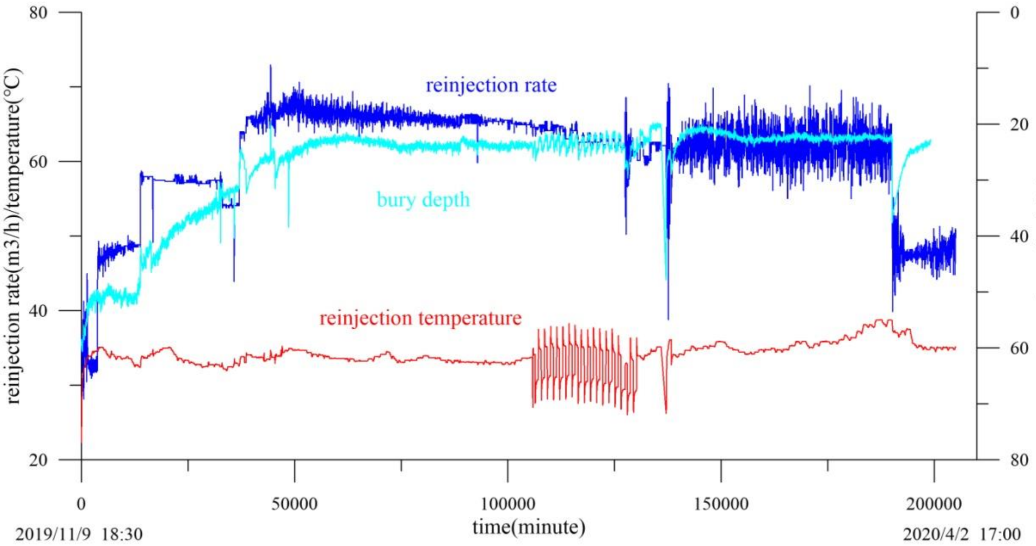

Figure. 15 the reinjection temperature, reinjection rate and reinjection pressure at 2019-2020

3.2.5 Reinjection in 2020-2021 heating season

The project started to test the readiness of the heating service facilities at November 6th 2020 for the 2020-2021 heating season, and there is a malfunction problem of the pump at 2020/11/9 16:00, the malfunctioned pump was replaced by a new pump. The project started officially provide heating service at 2020/11/11 14:30. The pumping rate was controlled manually according to the weather, the reinjection rate complied with the pumping rate, which stepped gradually up from 56 m^3/h to around 70 m^3/h at the early period of the heating season, and remained around 70 m^3/h till 2021/1/26. Then the reinjection rate drop to around 62 m^3/h from 2021/1/26 to 2021/3/9, and around 56 m^3/h from 2021/3/9 to 2021/3/26.

The temperature of the reinjected geothermal tail water is around 35℃. The initial water level bury depth at the reinjection well was 76.86m , the water level in the reinjection well rose gradually at the early stage of the reinjection, then remain near constant at a bury depth of 45m, no extra pressure was need to maintain the reinjection(Fig.16). The total reinjected geothermal tail water is about 204 400 m^3 in 2020-2021 heating season.

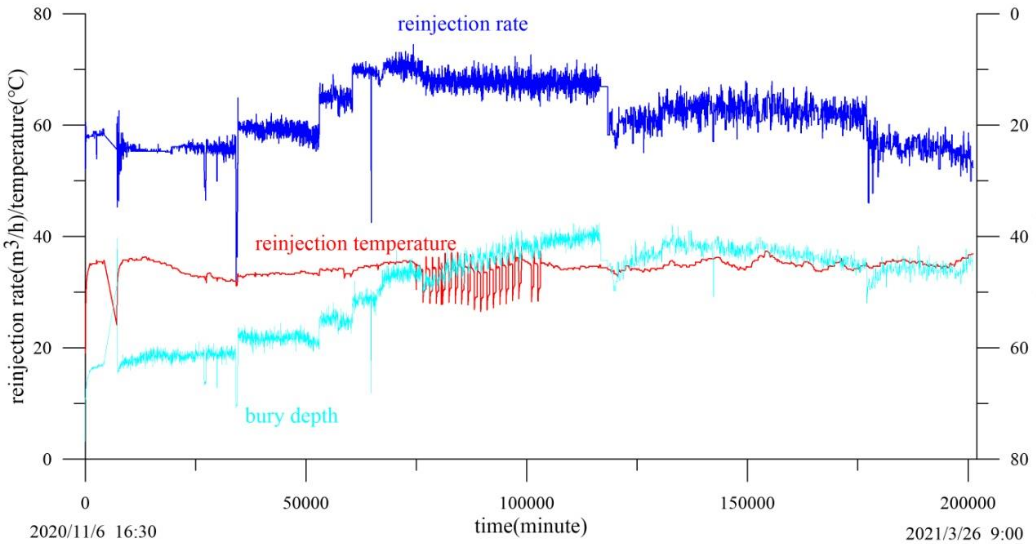

Figure. 16 the reinjection temperature, reinjection rate and reinjection pressure at 2020-2021

3.2.6 Reinjection in 2021-2022 heating season

The project started to provide heating service at November 7th 2021 for the 2021-2022 heating season. The pumping rate was controlled manually according to the weather, the reinjection rate complied with the pumping rate, there are briefly three stages of reinjection rate, the reinjection rate is about 50 m^3/h at the first stage from 2021/11/7 to 2021/12/24, and is about 70 m^3/h at the second stage from 2021/12/24 to 2022/3/1, and about 41 m^3/h at the third stage from 2022/3/1 to 2022/4/5. The temperature of the reinjected geothermal tail water is around 33℃. The initial water level bury depth at the reinjection well was 81.18m , at the first stage of the reinjection ,the water level in the reinjection well rose almost instantly to the bury depth of 60m, then gradually rose the bury depth to 53m, and then gradually down the bury depth of 65m. At the second stage, the water level rose gradually with the progression of reinjection to the bury depth of 18.51m. At the third stage, the average water level bury depth was around 40m. No extra pressure was needed to maintain the reinjection(Fig.17). The total reinjected geothermal tail water is about 204 900 m^3 in 2021-2022 heating season.

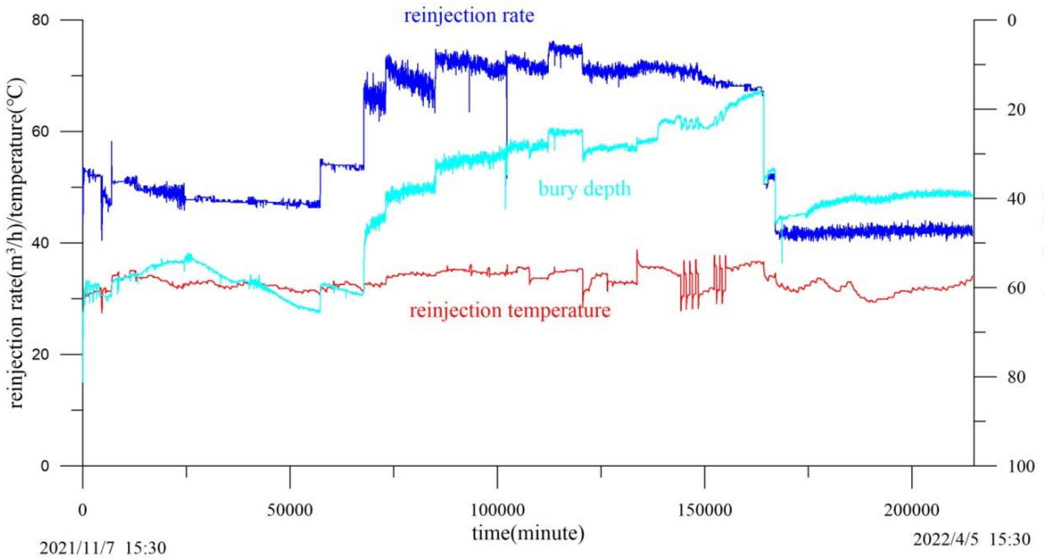

Figure. 17 The reinjection temperature, reinjection rate and reinjection pressure at 2021-2022

3.3 Tracer test

3.3.1 Method for tracer amount calculation

Tracer test is a valuable tool to understand the inter-well connectivity between the reinjection well and production well, to detect flow channel and flow velocity, and predict possible cooling of production wells in long term reinjection practice (Pang *et al*, 2014) 。Based on total dilution model, the least amount of tracer for the tracer test can be calculated from the following formula(Zhao et al, 2021):

$$G = \pi R^2 H \emptyset S \qquad (1)$$

$$M = G \times \frac{M_s}{nYM_a} \qquad (2)$$

Where G is the least amount of tracer element (kg); R is the distance between the tracer injection well and observation well (m); H is the average thickness of the geothermal reservoir (m); $\emptyset$ is the porosity of the geothermal reservoir (%); S is the sensitivity of the detection apparatus (mg/l); M is the least amount of tracer substance contain tracer element (kg); M_s is the molecular weight of tracer substance (g/mol); n is the number of tracer element in the molecule of tracer substance. Y is the purity of the tracer substance (%); M_a is the molecular weight of the tracer element (g/mol).

By analyzing the hiding philosophy of the formula (1), revealed that the least amount of tracer is to raise the concentration of tracer element in the reservoir cylinder with a radius of R and height of H, to 1000 times of the concentration of sensitivity of the detection apparatus.

3.3.2 Molybdenum tracer test

A tracer test had been carried out during 2016 by using Hexaammonium molybdate [$(NH_4)_6Mo_7O_{24}\cdot 4H_2O$] as tracer substance.

3.3.2.1 Tracer dosage

By consulting the intended laboratory about the sensitivity of the detection apparatus for Molybdenum (Mo), the apparatus used is Inductively coupled plasma mass spectrometry with S of 0.0001mg/l. obtained from the lithological information revealed by the reinjection well and production well, the porosity of the geothermal reservoir is about 30%, the average thickness of the geothermal reservoir is about 150m. Substitute those values into the formula (1) gain the least amount of tracer Molybdenum is：

G=3.1416*172.5*172.5*150*30%*0.0001=420.67kg

The tracer substance is Hexaammonium molybdate, the purity of it is 98%, the least amount of Hexaammonium molybdate is:

$$\mathrm{M} = 420.67 \times \frac{1235.58}{7 \times 98\% \times 95.94} = 789.75 \text{ kg}$$

3.3.2.2 Tracer test result

800 kg of Hexaammonium molybdate [$(NH_4)_6Mo_7O_{24}\cdot 4H_2O$] was pumped into the reinjection well during December 14th 2016 12:00 to 14:30. The background concentration of molybdenum cation in the geothermal water is about 0.011 mg/l. The movement mechanism of the tracer is complex, governed combined by the porous flow and molecular diffusion activity. During the heating season, driving by the high hydraulic potential difference between the production well and reinjection well, the tracer movement is dominantly govern by porous flow, whereas during the off heating season, though there is a slight porous flow from reinjection well to pumping well caused by the lag effect, the tracer movement is driven by the concentration difference towards to the pumping well. The molybdenum cation concentration was regularly sampled and tested from the production well's outlet, the molybdenum concentration were fluctuated around 0.01mg/l during the first three heating seasons, then an abrupt rise in concentration at the beginning of the fourth heating season to around 0.04mg/l at 557010 minute from the tracer injection time neglecting the time spans of off heating seasons(Fig.18). The shape of the molybdenum concentration curve is unlike the ideal shape of tracer concentration curve(Graham and John, 2014), after the first peak followed by an abrupt lower trough, then the concentration follow an upward trend. The curve shows three abrupt concentration risings, the peak concentration time still unclear.

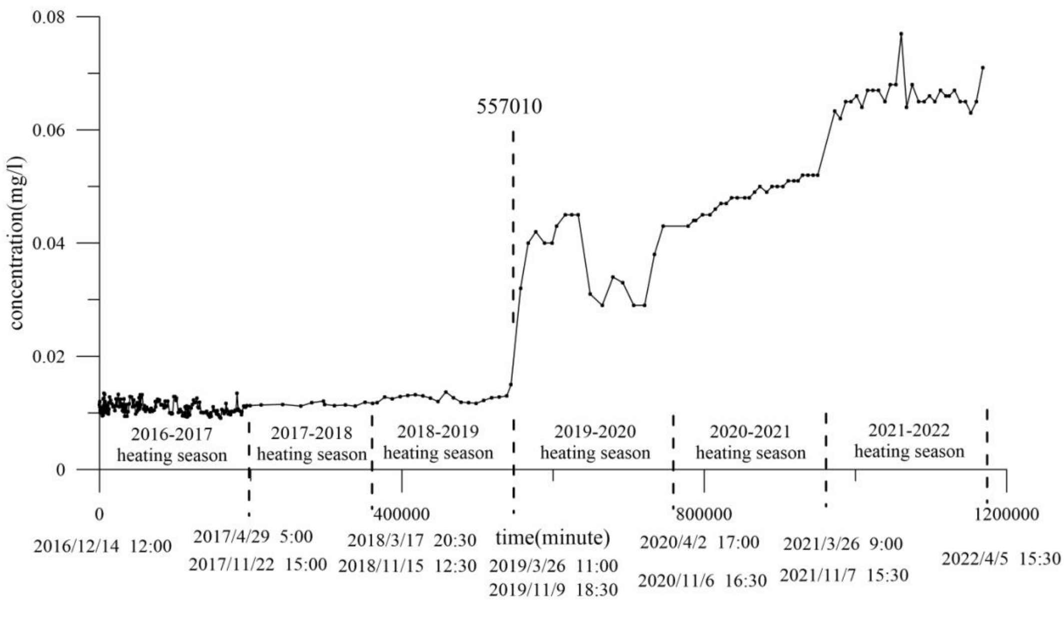

Figure. 18 Molybdenum concentration versus time curve during heating seasons

3.3.2.3 Tracer test interpretation

Informed from the molybdenum concentration curve, there are may exist several flow paths from injection well to the production well, the travel speed of the reinjected geothermal tail water through the main path is as following:

$u = \frac{l}{t} = \frac{172.5 \times 60 \times 24}{557010}$=0.446m/d

3.4 Temperature logging

3.4.1 Temperature logging data

To understand the temperature change pattern in the geothermal reservoir caused by reinjection, series of well temperature logging were carried out at the reinjection well during off heating seasons, the temperature was measured downhole at an interval of 5 meter, the accuracy of the apparatus is 0.1℃ (Fig.19, Fig.20, Fig.21, Fig.22, Fig.23). Generally, the logging curves show two abrupt temperature changes at the water table surface of the geothermal water and at the top the geothermal reservoir. The temperature above the water table is affected by the atmospheric temperature changes. Except for the year 2017, which was affected by the high temperature geothermal water reinjection after the heating season, there is an obvious cross point for the curves. At the cross point, the temperature of the reinjected geothermal tail water equals to the temperature of the strata. Above the cross point, the measured temperature decreases with time at the same depth, which may because by the temperature of the reinjected geothermal tail water is higher than the temperature of the strata, the reinjection activity warmed up the strata near the well casing, and then cooling down after reinjection result from the heat exchange between the adjacent strata mass. But below the cross point, the measured temperature increases with time at the same depth, which indicated that the temperature of the strata is higher than that of the reinjected geothermal tail water. The temperature logging curve line is not even, may caused by the intercalated distribution of the sand and clay strata. Generally, the sand strata response quick to the temperature change than clay strata. When enter the geothermal reservoir, the logging temperature drops to near the temperature of reinjected geothermal tail water. The logging temperature increase with time suggest that there is heat replenishment from surround strata mass, the higher temperature rise rate zones may due heat convection in the geothermal reservoir sections.

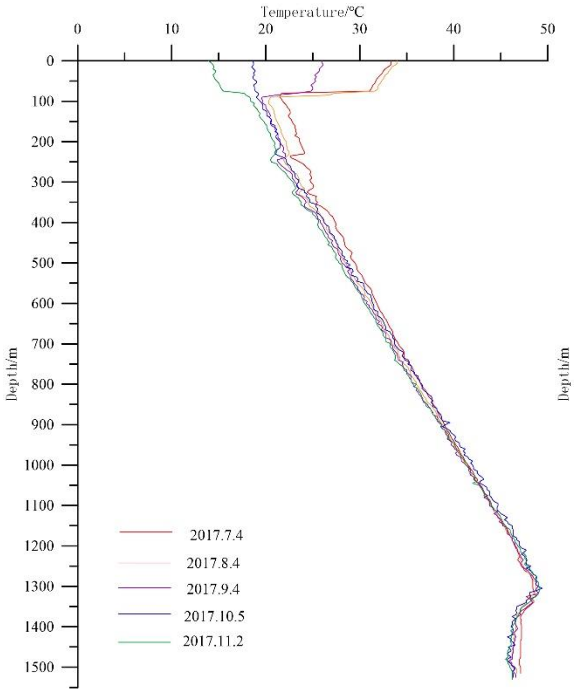

Figure 19. Temperature logging in 2017

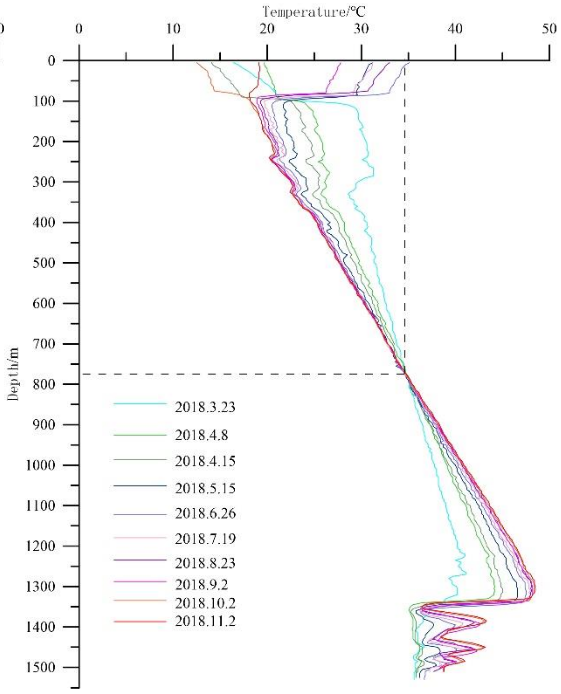

Figure 20. Temperature logging in 2018

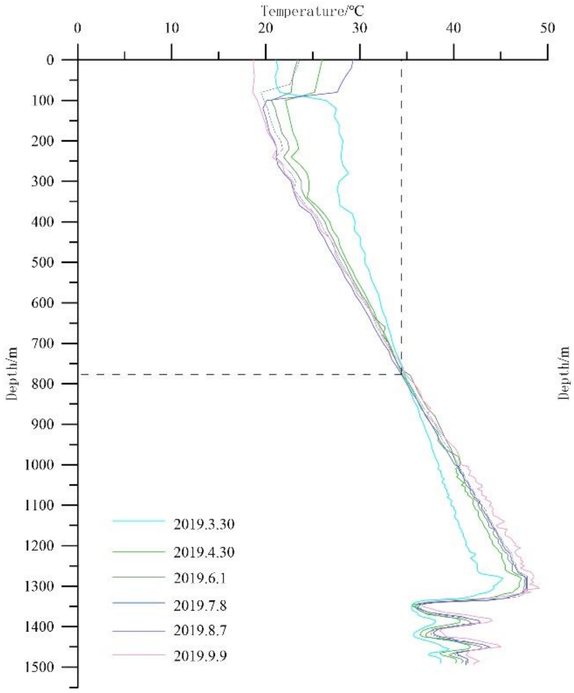

Figure 21. Temperature logging in 2019

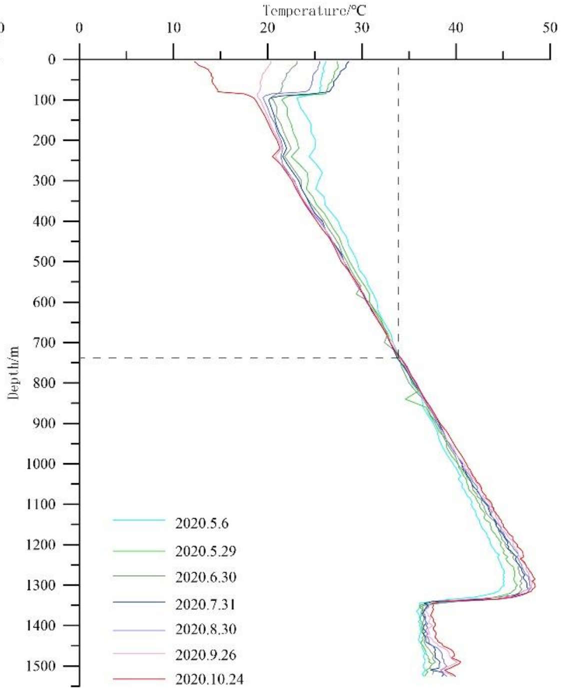

Figure 22. Temperature logging in 2020

3.4.2 Temperature change pattern in the geothermal reservoir

To analyze the temperature change pattern in the geothermal reservoir, we check the temperature variations in the temperature logging curve below depth 1300m, which is about the bury depth of the top of the gravel pack. The temperature logging data taken in 2017 were affected by the reinjection of higher temperature geothermal water at the later stage, the temperature curves shows a cooling trend of reservoir temperature versus time, which may caused by the mixing of cooler reinjected geothermal tail water with the higher temperature geothermal water reinjected, indicates that the heat replenished from the heat exchanging with the ambient geologic body and from the terrestrial heat flow underneath was far less to meet the needs of heating up the cooler reinjected geothermal tail water.

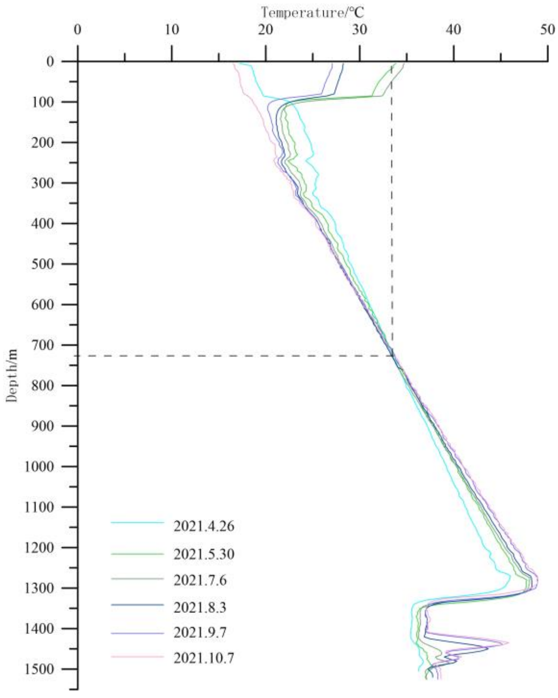

Figure 23. Temperature logging in 2021

The temperature logging data taken in 2018 to 2021 revealed that the temperature of the geothermal reservoir was gradually warm up with time during off heating season, indicated there is heat replenishment from the ambient rock mass. Read from the shapes of the curves, there are three obvious temperature rising peaks in 2018 and 2019 logging curves, which may stand for three main sandstone layers in the geothermal reservoir, the temperature rising was caused by the convection heat transferring of geothermal water in the geothermal reservoir. While there is only one temperature rising peak remained in the bottom part of the 2020 and 2021 logging curves, which may suggest that the reinjected cooler geothermal tail water has moved far from the reinjection well at the upper section of the geothermal reservoir, but at the lower section of the geothermal reservoir, the reinjected cooler geothermal tail water has not moved far enough, so the convection heat transferring still prevail.

4 CONCLUSION

(1)The geothermal reservoir been exploited is the lower part of the Guantao sandstone geothermal reservoir. The project has a doublet of one production well and one reinjection well , the reservoir composed of several layers of sandstone strata, intercalated by mudstone strata, the thickness of the sandstone strata vary greatly between the two wells with about 160m revealed by the reinjection well and about 85m disclosed by the production well.

(2) The storativity of the geothermal reservoir is 2.74E-4 to 7.70E-4, and the transmissivity of geothermal reservoir is 194 to 784 m^2/d.

(3) The project has conducted 6 years of near 100% reinjection rate of geothermal tail water without pressurization, the total reinjected geothermal tail water amount to 1 129 200m^3, which suggested that long term reinjection in the sandstone geothermal reservoir is viable.

(4) There are several flow paths from the reinjection well to the production well, the travel speed of the reinjected geothermal tail water through the main path is about 0.446m/d.

(5) There is heat replenishment from the ambient rock mass to the geothermal reservoir been cooled by reinjection, but the heat replenished from the heat exchanging with the ambient geologic body and from the terrestrial heat flow underneath was far less to meet the needs of heating up the cooler reinjected geothermal tail water.

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