LECTURE 5

EXPERIENCE OF GEOTHERMAL REINJECTION IN TIANJIN AND BEIJING

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ABSTRACT

Reinjection has been widely applied in management of geothermal resources, and has become one of the routine applications of geothermal development in many geothermal fields. In China, reinjection tests started in 1974 in Beijing. But large scale reinjection of the geothermal waste water from heating systems was started in Tianjin in 1990’s. Since 2000, reinjection has been considered an increasingly important aspect of geothermal resources management in Beijing and Tianjin. At present, a number of reinjection projects are in operation in Tianjin and Beijing. As a result, the water level declining of geothermal wells has been greatly diminished. In Xiaotangshan geothermal field in Beijing, the water level has accurately stopped declining, since 2006, owing to reinjection and control on production of geothermal water.

In this paper, the reinjection history in Tianjin and Beijing will be summarized, and the experiences and problems of reinjection, including the distances between the production and reinjection wells, tracer test and monitoring of geothermal fields with reinjection, will be discussed.

1. INTRODUCTION

Geothermal is an environmentally benign energy source, widely used in many countries for power generation and direct use purposes, such as in space heating, bathing, swimming pools, fish farming, greenhouses, health spas and recreational facilities etc., bringing about significant economical and environmental benefits. Geothermal is a type of renewable energy, but it should not be over-exploited; or, the resources will be depleted, and will need a relatively long time to recover from improper management. Therefore, it is mandatory to implement proper management for the sustainable use of geothermal resources.

Reinjection has been widely used in the management of geothermal fields, and is becoming a routine application in many geothermal fields, since the first reinjection project was implemented in the famous Geysers area in 1969 (Axelsson & Stefansson, 1999). The purpose of geothermal reinjection
is for (1) disposal of the waste geothermal fluid that may cause thermal and chemical pollution; (2) improvement of heat mining. Over 90% of the heat in the geothermal reservoirs is stored in the hot rock matrix; (3) stabilization of the production capacity of the geothermal field through the maintenance of the reservoir pressure (Liu, 1999).

Geothermal reinjection began as a method of disposing of wastewater from power plants in order to protect the surrounding environment. It was initialized as early as 1969 and 1970 at the Geysers area in California and in the Ahuachapán field in El Salvador, respectively. Presently there are a number of geothermal fields worldwide where reinjection is already a part of the operation, including the Geysers field in USA, the Larderello field in Italy, the Berlin field in El Salvador, the Paris field in France, the Laugaland field in North Iceland etc. There are a number of other geothermal fields where reinjection tests have been carried out, and some of them may start production-scale reinjection soon.

There are abundant low enthalpy geothermal resources in China (high enthalpy geothermal only exists in Tibet and Taiwan). The resources are mostly used for health spas and recreation in southern China where there is no need for heating in the winter; in northern China, where the climate is colder, the resources are used for space heating and various other direct. For the past 30 years, geothermal utilization has been ever increasing, especially in the past 10 years and in large northern cities such as Beijing, Tianjin and Xi’an etc. With the expansion of geothermal utilization, some problems have arisen, i.e. the rapid decline of reservoir pressure in geothermal fields where the production is high. Reinjection is, therefore, considered as a measure for the sustainable use of geothermal energy.

In China, the earliest geothermal reinjection tests were started in the urban area of Beijing in 1974 and 1975. In 1980, a larger scale reinjection tests were carried out in this geothermal area: cold ground water and return geothermal water was reinjected into a geothermal well with a depth of 1275 m. At the end of the 1980’s, reinjection tests were carried out in the Tertiary sandstone reservoir in Tianjin. Since 1996, reinjection tests have also been implemented in the dolomite reservoir in Tianjin. Till now, there have been 13 production-reinjection doublets running in Tianjin. In 2004 and 2005, reinjection tests into the sandstone reservoir were carried out in Tianjin again. In 2001, reinjection tests were implemented in Xiaotanshan geothermal field north of Beijing, and in the Urban geothermal field in Beijing. Since then, production scale reinjection has been running in Xiaotangshan Geothermal field. Tests in both Tianjin and Beijing showed that reinjection is a feasible measure to ensure the sustainable use of geothermal resources in the two cities.

2. THE IMPORTANCE OF GEOTHERMAL REINJECTION

Beijing is rich in low-temperature geothermal, stored in limestone and dolomite reservoirs, and the identified area with geothermal potential is greater than 2760 km², divided on 10 geothermal fields, such as the ones in the southeast Urban area and Xiaotangshan (about 30 km north of the city centre). The temperature of the geothermal water in Beijing is 38-89°C. The geothermal water contains SiO₂ and other components that are good for human skin. Historically, hot spring water was used for bathing and for spas in Beijing. Large-scale geothermal use started in 1971 in Beijing, with the completion of the first geothermal well. After that, the number of geothermal wells increased rapidly, and the amount of geothermal water production increased with it. By 1985, the geothermal production increased to over 10 million m³ annually, causing a rapid declining of reservoir pressure (water level). Therefore, strict measures were taken to control the amount of geothermal water subtraction since 1985. As a result, the water level decline has slowed down (Figure 1). At present, it is generally between 1 and 2.5 m annually, and it still threatens the sustainability of geothermal utilization in Beijing.

This means that the net discharge of geothermal water, that is, the interval between production and reinjection of the geothermal systems should be under a certain limit. Otherwise, the water level of the geothermal wells will decline, and threaten the sustainability of the geothermal resource. It also
Experience of reinjection means that if reinjection will not be carried out, the production should be lowered drastically. Therefore, it is essential to reinject the used geothermal water back into the geothermal reservoir.

The geothermal resources in Tianjin are low-enthalpy geothermal resources in sedimentary basins. The area with geothermal potential is about 8700 km², accounting for about 77% of the total area of the city. Geothermal water is stored in the Tertiary sandstone and karst-fractured dolomite. The temperature of the geothermal water ranges from 55 to 103°C. Geothermal is widely used for space heating, domestic hot water, fish farming and greenhouse, recreation etc. By the end of 2007, 294 geothermal wells (including 38 reinjection wells) were drilled in Tianjin, the deepest well being close to 4000 m deep. The production capacity of each well is 100-200 m³/h. The annual production of geothermal water is 24.50 Mm³.

Due to the large-scale development of the geothermal resources, the reservoir pressure decreases quickly in Tianjin, especially in the dolomite reservoir. Since 1997, the annual water level drawdown has been over 3 m. Currently the depth to the static water level in the geothermal wells varies between -40 m and -90 m, with an annual drawdown of 6-9 m (Figure 2). This suggests that the recharge to the reservoirs is rather limited. Meanwhile, the water level drawdown is lower than before 2004, due to the incrimination of the reinjection rate. Therefore, it is necessary to implement reinjection for maintaining the reservoir pressure and prolonging the life time of the geothermal wells.

3. APPLICATION IN TIANJIN

3.1 History of reinjection in Tianjin

Reinjection activity started in the early 1980’s in Tianjin, and the history can be divided into 4 periods:

3.1.1 1980 - 1995

With the increase of geothermal water production, it was realized that reinjection might be a useful way to control the declining water level. In the beginning of the 1980’s, studies on geothermal
Production-reinjection doublet or production-reinjection well groups were carried out, and related numerical modelling on sandstone reinjection was conducted. Based on the results, reinjection tests, focused on reinjection into sandstone in the geothermal reservoir of the Tertiary System, were carried out in Dagang and Tanggu District in 1987-1989 and in 1995.

### 3.1.2 1995 - 1998

With the increase of geothermal water use from the dolomite reservoir, more attention was paid on reinjection into the dolomite reservoir in Tianjin. In 1995, the first production-reinjection doublet was drilled, and reinjection test was carried out in 1996-1997. The result showed that reinjection is technically feasible in the dolomite geothermal reservoir in Tianjin (Wang et al., 2001).

### 3.1.3 1998 - present

Based on the results of the reinjection tests for the dolomite reservoir, a few production and reinjection doublets were installed and operated in this period in Tianjin. In the same period of time, tracer tests were carried out for better understanding the movement and heating processes of the reinjected water. Monitoring of the doublets has become a routine, including flow rate, water level, temperature, and chemical contents. Numerical modelling was carried out for predicting the effect of reinjection. A technical standard for design and operation of geothermal reinjection was compiled, by summarizing the experiences of geothermal reinjection in Tianjin. Since 2004, tests on reinjection into sandstone reservoirs were started again in Tianjin, due to the rapid decline of the water level in the sandstone reservoir.

### 3.2 Reinjection in dolomite reservoir

Most of the geothermal production/reinjection doublet systems in Tianjin are inside the urban area. Both of the production and reinjection wells were drilled into the dolomite reservoir which is widely dispersed in the Tianjin area (Wang et al., 2001).

Since the first geothermal production-reinjection doublet was put into operation during the winter (during the space-heating period) of 1999, 27 reinjection wells and 77 production wells have been
drilled in this reservoir in Tianjin. All the doublet systems reinject under artesian conditions. All the geothermal water from the doublets is reinjected into the reservoir after the heating cycle. The amount of reinjection was $2.89 \times 10^6$ m$^3$ in 2007, accounting for about 24% of the total production from the geothermal reservoir. Although, that there are more geothermal production wells used for space heating than there are reinjection wells, and that production wells adjacent to reinjection wells influence the reservoir pressure around the reinjection wells, it can be observed that the water level close to reinjection wells declines much slower than in other parts. The average annual drawdown has decreased with increasing reinjection rates. Still, there have been no observable temperature changes in the surrounding production wells.

According to the geological conditions and the past 20 years of production history, a numerical model was set up for the geothermal system in the urban area in Tianjin, using the software package TOUGH2. The model was used to predict the changes of reservoir pressure in the geothermal system in the future, assuming that (1) all the geothermal wells will keep the average production rate in 2002 (80-120 m$^3$/h in winter, and 5-10% of the winter production rate in the summer); (2) all the 10 reinjection wells are put into use with a reinjection rate of 50-100 m$^3$/h for each well, and the annual amount of production is 1.3716$\times 10^7$ m$^3$ (deducting the amount of reinjection 1.7$\times 10^6$ m$^3$). It was predicted that the deepest water level in the reservoir will be 193 m below sea level. This means that the sustainability of the geothermal production cannot be realized if the present production and reinjection will be maintained in the future. If the present amount of reinjection increases with 150%, it was predicted that the deepest water level will be 138 m below see level in 2013 (Figure 3). This means that reinjection makes an effective measure to counteract the decline in reservoir pressure (Wang et al., 2005).

### 3.3 Tracer test

Reinjected cold water can extract additional thermal energy from the rock matrix and improve the heat mining from the geothermal reservoir. But it is not a simple decision to increase the amount of reinjection, because of the possible cooling of the production water. It is proposed that tracer test be carried out to study the connections between the production and reinjection wells and to predict the cooling effect by the increase of reinjection.

#### 3.3.1 Tracer test in the winter of 1998 - 1999

To investigate the connections between the reinjection and production wells of the WR45 doublet, a tracer test was conducted in the winter of 1998-1999. 10 kg of potassium iodide (KI) was selected as
the tracer. Meanwhile the chemical content of the water produced from the surrounding wells was monitored carefully. The resulting data are presented in Figure 4.

The monitoring data shows that the tracer concentration is almost constant in the production well, i.e. no noticeable recovery. On the other hand observation well GC45-2 shows some iodine recovery. This means that the hydrological connection between the production and reinjection well of doublet WR45 is indirect, but that there may be a direct (fast migration) channel between the reinjection well and other nearby geothermal production wells (such as production well GC45-1, which is about 2.5 km away from the reinjection well).

A mathematical model simulated the results from GC45-2 tries and assesses the nature and structure of the fractures connecting GC45-2 and the reinjection well. Figure 5 and Table 1 show the simulated recovery and model parameters, respectively. The simulation curve is composed of 4 pulses, corresponding to 4 flow channels/fractures. When the tracer was reinjected into the aquifer, it travelled rapidly along the most direct path, which had the smallest cross section. For this channel the tracer moved quickly to the production well and reached the maximum concentration in a very short
Experience of reinjection

If, on the other hand, the reinjected water diffuses into a large reservoir volume, only a small fraction of the tracer will be recovered and the time it takes it to reach peak value will be much longer. In the latter case, the thermal breakthrough time will not be a problem for the doublet system operation. Therefore, tracer tests are very important for understanding the mode of transport, flow channels, and fracture characteristics in the doublet production/reinjection systems.

<table>
<thead>
<tr>
<th>Cross-section area $A$ (m$^2$)</th>
<th>Dispersivity $\alpha_L$ (m)</th>
<th>Mass recovered (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fissure 1</td>
<td>1.50</td>
<td>356</td>
</tr>
<tr>
<td>Fissure 2</td>
<td>15.7</td>
<td>142</td>
</tr>
<tr>
<td>Fissure 3</td>
<td>29.5</td>
<td>10.1</td>
</tr>
<tr>
<td>Fissure 4</td>
<td>54.7</td>
<td>162</td>
</tr>
</tbody>
</table>

**TABLE 1:** Calculated parameters of the tracer test

3.3.2 Tracer test in 2001

In the winter of 2001, another tracer test in the dolomite reservoir was carried out and the tracer used was the radioactive isotopic tracer ($^{125}$I, $^{35}$S). The distance between the production and the observation well is more than 4km. The amount of tracer used was 350 mCi ($1.3\times10^{10}$Bq, $^{125}$I). The entire tracer was applied instantaneously. The tracer breakthrough time was about 3 days, and the peak time was at about 52 days (Figure 6). According to the deduction from the tracer tests, there is no premature thermal break through.

3.4 Reinjection in sandstone reservoir

Through many years of research, the reinjection problems of dolomite reservoir have basically been solved. But the reinjection problems of sandstone reservoirs still exist, mainly at low reinjection rates and short duration times. The production from sandstone reservoirs exceeds 50% of the total geothermal production in Tianjin. Thus it is important to resolve the reinjection problems for the sustainable development and utilization of geothermal resources in Tianjin.
By the end of the 1980s, reinjection tests had been carried out in Tertiary sandstone reservoirs in Tianjin. During the tests about 30-50 m$^3$/h waste water was reinjected into the reservoir. But along with the reinjection, the reinjectivity quickly decreased. Tests of sandstone reinjection were carried out again in the winter of 2004-2005, and the results were similar to that of the previous tests. The reinjection tests were carried out in the Neogene Guantao formation sandstone reservoir in the Wuqing District, the Dongli District and the Dagang District, and reinjection well drilling technology, reinjection plugging problems and ground reinjection systems were studied here.

During the late Oligocene, North China Plain rose to the dustpan basin. And in the Miocene period the Yanshan uplift zone became the main source area. Because of the transport and deposition in lower river bends and braided rivers, clastic rocks formations arose of fluvial facies. It finally formed alluvial-pluvial fans and fluvial deposits well-distributed on the North China Plain. They mainly include mottle silt rocks and sand gravel rocks. The Neogene Guantao formation ultimately formed from clastic fluvial rocks with obvious sedimentary cycles, and they are mainly located in the Wuqing sag and the Huanghua depression in Tianjin. Clastic rocks in Tanggu, Beitang and the northwest of Xiaozhan are mainly of gravel facies, other parts are mainly of gravel and sand facies.

The top of the Guantao formation is a thick sand layer, the bottom is a gravel sand layer and its middle part is a silt stone layer. The total thickness is 200-600 m, of which the sand and gravel thickness amounts to 70-360 m. The porosity of the formation is 15%-32.4% and its permeability is 773-2631×10^{-3}$ μm$^2$. There is a well-formed gravel layer at the bottom of the Guantao formation, with a thickness of 30-60 m and a gravel diameter of 5 mm. The mean porosity is about 20%. Through exploration, deterring physical properties of rock samples, analyzing geothermal conditions and hydrological conditions, it is evident that the Guantao formation is a mid-low temperature heat storage layer created by normal consolidation processes. It also apparent that the source of its heat is from deep heat conduction and its water supply is from lateral runoff recharge.

The main problem with sandstone reinjection in Tianjin is that the reinjectivity decreases fast with time, or the reinjectivity changes too much with time during the reinjection process. The clogging of reinjection wells is attributed to physical, chemical and biological factors.

### 3.4.1 Physical plugging

The filtered particles from the reinjection water has been analyzed by SEM (Scanning Electronic Microprobe) and X-ray diffraction in most of the wells. The result indicate that plagioclase, quartz, K-feldspar, FeS and ZnS seem to be the most common components carried on by the fluid, plus a certain number of possible other components, such as NaCl, CaCO$_3$, etc.

### 3.4.2 Chemical plugging

There seem to be three types of minerals that potentially may precipitate during reinjection around the well bottom: quartz (chalcedony), calcite, Fe-Zn oxides (hydroxides) and sulphides. Among them, the Fe-Zn oxide and the sulphide have been found in samples of 25 wells. Also similar components have been discovered in filtration. This proves that the water is saturation in these components in these exploitation wells. It is assumed that iron and zinc comes from oxidation of the well tube and water conveying pipeline.

In order to prevent the suspended solid particle from entering the reservoir, and from博客ing the passage, referring to successful experiences of water reinjection in oil wells, double deck cage screens is used when filling gravel into the geothermal well.

Meanwhile, In order to prevent physical and chemical jam, use is made of secondary filtration equipment in the reinjection system. The primary filtration is rough, the precision is of 50 μm, whereas, the secondary filtration is fine, with a precision of 3-5 μm. There are pressure cabins at the ends of the filtration pot. If there is a pressure difference in the cabins the finer particles will resort in
the filter pack. In practice, the precision of the secondary filtration is high and its effect is good. To prevent gas blockage, there is a vent installed at the head of the reinjection well.

Two test sites were established in the Wuqing and Dongli districts, in 2004. Here, two reinjection wells have been drilled in the Guantao group reservoir. The two level filter system was used in the ground reinjection system, and productive reinjection tests have been conducted. In the Wuqing district the temperature of the reinjected fluid is 42 ~ 52°C, pumped at a reinjection rate with a decrease from 49 m³/h to 20 m³/h. The stable water level is at about 10 m depth. In the Dongli district the temperature of the reinjected fluid is 50°C, with a reinjection rate of about 16 m³/h. The stable water level here is at about 15 m depth.

In summary, through the study of reinjection well-drilling technology and ground reinjection systems, some problems of physical and chemical reinjection plugging have been resolved, but decreasing reinjection rates remain a problem.

4. APPLICATION IN BEIJING

4.1 History of reinjection in Beijing

In China, the earliest geothermal reinjection tests were started in the urban area of Beijing in 1974 and 1975. In 1980, larger scale reinjection tests were carried out in the geothermal area: cold ground water and return geothermal water was reinjected into a geothermal well at a depth of 1275 m. Hereafter, reinjection stopped in Beijing for a rather long time. In 2001, reinjection tests and demonstration projects started again. Recently, reinjection has been implemented on rather large scales and received significant results in Beijing. The geothermal reinjection history can be divided into 4 periods.

4.1.1 1974-1983

Because of the increase of geothermal water production in the early 1970’s, the water level of the geothermal wells declined rather fast. It was considered that reinjection would be an important measure to prolong the lifetime of the geothermal wells. In 1974, a short reinjection test was conducted in the famous Park of the Temple of Heaven in the southeast urban area. And in 1975, a short reinjection test was conducted again in the southeast urban area.

Until 1980, there were more than 30 geothermal wells in the southeast part of Beijing, the geothermal water production was about 3 million m³/a, and the water level declining became more serious. Therefore, a larger scale reinjection test was carried out from June 4 to September 2, 1980. Cold groundwater of 15.5°C was reinjected into a 1060 m deep geothermal well in the southeast Urban area. In the 89 days of the reinjection test, about 60,000 m³ of cold water was reinjected, and the temperature change inside the reinjection well was observed (Liu et al., 1981). After the 89 days, 40°C return geothermal water from a heating system was reinjected into a 1274.65 m deep geothermal well in the same area (Bai and Gong, 1984). In that period, reinjection tests focused on the time needed for the reinjected water to return to reservoir temperatures.

4.1.2 1983-2000

Geothermal reinjection activity stopped mostly because of financial problems, although the water level continued to decline in this period.

4.1.3 2001-2002

After 1999, with the fast development of geothermal utilization in Beijing, and the wide recognition of sustainable development, reinjection was again considered to counter the declining of water level
drawdown. In 2001, a demonstration project of geothermal reinjection was carried out in the Xiaotangshan area. Return water from geothermal heating was reinjected back to the same geothermal reservoir through a well about 200 m away from the production well. This reinjection project operated smoothly in 2001 and 2002, and no cooling of the production temperature was observed (Liu, 2003).

In 2001, a reinjection test was also conducted in the southeast urban area in Beijing. Return water from a heating system was reinjected into a well that strikes a shallower geothermal reservoir 80 m away from the production well. Reinjection tests also started in 2002 at the south-eastern boarder of the same geothermal field (Liu, 2003).

4.1.4 2003-present

Since 2003, reinjection in Beijing has expanded rapidly. In the Xiaotangshan area, there were 6 reinjection wells in operation in 2006, and the amount of water reinjected was about 60% of the total production. Reinjection also expanded in other parts of Beijing during this period, and the role of reinjection in sustainable utilization of geothermal resources has been acknowledged.

4.2 Reinjection in the Xiaotangshan area

The reinjection in the Xiaotansgan began in 2001 in a hotel in the central part of the geothermal field. One of the two production wells at the hotel was converted into a reinjection well. The wells of the hotel were drilled in 1984 and 1996, respectively. The distance between the wells is about 200 m. The geothermal reservoir is in limestone of the Cambrian System and the dolomite of the Jixian System. The wells come across the same fault which is very important structure to the occurrence of geothermal in the vicinity of hotel. The reinjection was carried out from November 30, 2001 to March 27, 2002. In total 117 days. The temperature of the reinjected return water was 30-44°C. The flow rate of reinjection changed with the atmospheric temperature; it was approximately 800 m³/d on the coldest days from January 8 to 20, 2002, and under 800 m³/d on other days. The reinjectivity of the well did not decrease during the reinjection (Figure 7). The total amount of water reinjected was 73,331 m³ for the duration of the heating season (Liu and Yan, 2006).

![FIGURE 7: reinjection volume and water level changes of a reinjection well in the Xiaotangshan Geothermal Field during the heating season of 2001-2002](image-url)
A tracer test was conducted during this reinjection test mentioned above. On January 8, 2002, 50 kg of KI was applied to the reinjection well instantaneously, 39 days after the reinjection started. 165 water samples from the production well were collected until space heating stopped. Samples were also collected from surrounding wells. No iodine was found in the samples. This indicates that there is not a direct pass between the reinjection and production wells, and that premature thermal breakthrough is not likely to happen in the production well (Liu, 2002).

When reinjection stopped, a submersible pump was installed in the reinjection well, intended to restore the reinjectivity of the well, in case of reduction. On April 15, 2002, the pump was started. At the beginning, the temperature of the water was around 30°C, and in an hour, the temperature rose to 63.5°C, and was thus nearly restored to its normal production temperature of 64°C. The reinjection test shows that the reinjectivity of the geothermal reservoir is rather good, and that the reservoir also has good capacity to reheat the reinjected colder water (Liu, 2006).

In the heating period of 2003-2004, a reinjection test was carried out in another hotel close to the one mentioned above. In 150 days, $1.48 \times 10^5$ m$^3$ of return water from the heating system was reinjected into a well drilled for reinjection purposes. The total amount of reinjection reached $2.48 \times 10^5$ m$^3$ throughout the heating season.

In the heating period of 2004-2005, four production-reinjection doublet systems were set up, by converting old production wells into reinjection wells, or by drilling new reinjection wells in the geothermal field. From November, 2004 to April, 2005, $10.2 \times 10^5$ m$^3$ of return water was reinjected into the geothermal reservoir, accounting for 36.5% of the total production (Liu and Yan, 2006).

In the heating period of 2005-2006, 6 reinjection wells were operating with return water from 8 production wells. There are two production-reinjection assemblages involving 2 production wells and 1 reinjection well each. The total quantity of reinjection was 1,322,778 m$^3$, accounting for 56.6% of the annual production in the field.

In 2001-2002, the effect of the reinjection on the stabilization of the reservoir pressure was very little, because the amount of reinjection was small. With the increase of reinjection, the effect became more and more significant. In the 5 months from December, 2004 to April, 2005, the water level of the monitoring well (has been monitored for about 30 years) was higher than that for the same period in 2003 and 2004 (Figure 8), i.e. it rose 2.5 m. Considering that the water level decreased 1 to 1.5 m every year before the large scale reinjection, the effect was noteworthy.

![FIGURE 8: The water level of a monitoring well in Xiaotangshan geothermal field from 2002 to 2006](image-url)
The reinjection in the Xiaotangshan geothermal field does not have observable influence on the temperature of the water in the production wells, although the distance between some of the production and reinjection wells is less than 200 m. It was also observed that the chemical composition of the geothermal water from the production wells did not change considerably. But the content of \( \text{HCO}_3^- \) in the water pumped from one of the reinjection wells decreased, and the content of \( \text{SO}_4^{2-} \) increased. This may indicate convection, where the reinjected cold (heavy) water flows to deeper levels of the geothermal reservoir and that the hot water (light) from greater depths flows to the top of the reservoir.

### 4.3 Reinjection in other area in Beijing

Although geothermal reinjection tests have been carried out as early as 1974 in the urban area in Beijing, long term reinjection only started in early 2002 in an apartment building district about 5 km south of Tiananmen Square. There are two geothermal reservoirs at different depths, both in dolomite, and separated by a shale layer of about 100 m thickness. Two wells, 90 m apart, were drilled in 2001 for the space heating of a 28,000 m² floor area (with the help of a heat pump system) and the reinjection of the return water from the heating system. The reinjection well is 1900 m deep, coming across the upper reservoir; the production well is 2054 m deep, completed for producing from the lower reservoir. The water temperatures from the reinjection well and the production well are 54°C and 59°C respectively. Both wells have good production capacity. The average flow rate of geothermal water in the heating system is 35 m³/h. When all the return water was reinjected into the upper reservoir and the water level in the reinjection well rose 4 m on average. The test showed that the reinjectivity of the well is close to its productivity. This geothermal heating system, incorporated reinjection and heat pumps, has been running for more than 6 years, and has not met any difficulties. It is also a good example for the cascaded use of geothermal resources (Liu, 2006).

Later, a few other reinjection wells were put into use in the southeast urban area and other geothermal fields in Beijing. Because the government encourages reinjection by subsidising, more developers are planning to start reinjection.

More tests and research, on wellhead facilities, and drilling and casing techniques of reinjection into sandstone reservoirs, are steadily progressing.

### 5. DISCUSSIONS

#### 5.1 Distance of production and reinjection

Cooling of the reservoir caused by reinjection of colder fluid has been reported in a few high-enthalphy geothermal fields. For low-enthalphy geothermal fields, there have not been any such reports, not even in cases where the distance between production wells and reinjection wells is rather small. Therefore, it may be concluded that for production/reinjection doublets in low-enthalphy geothermal fields, one does not have to fear about cooling of the reservoir, if the distance between production and reinjection wells is greater than a few hundred meters, and the amount of reinjection is kept to a limit.

In designing the distance between reinjection and production wells of a doublet system, a few factors should be considered, including the type of geothermal reservoir, the geological structures of the geothermal field, the permeability and thickness of the reservoir, the direction of fluid flow, the temperature difference between the reservoir and reinjection water, the flow rate of reinjection etc.

But in cases where large numbers of reinjection wells and production wells will be placed among in rather small area, care has to be taken, and proper testing and modelling have to be carried out before any such reinjection project is initialized, to avoid premature thermal breakthrough.
5.2 Tracer test

Tracer tests can be a very good precaution for thermal breakthrough. Tracer testing is one of the most important aspects of geothermal reinjection, and it now a routine. Tracer tests can provide information about the flow paths and the flow velocity of the geothermal fluids between the reinjection and production wells. For fractured reservoirs, the volume of the aperture can be deduced from the tests. This information can be used to predict the cooling due to reinjection (Axelsson and Stefánsson, 1999). For large-scale reinjection projects or a greater number of production and reinjection wells in a relatively small area, it is strongly proposed that tracer test be carried out.

5.3 Monitoring

Monitoring is one of the most important elements for geothermal management. For a geothermal field with reinjection, a proper monitoring program is even more important. Besides the monitoring of reservoir pressure, temperature, production volume, and hydrochemistry; water level in reinjection wells, temperature of reinjection water, reinjection volume, and hydrochemistry of reinjection water should also be monitored. The purpose is to uncover changes in the geothermal system caused by reinjection, especially cooling of the reservoir.

6. CONCLUDING REMARKS

Reinjection is one of the most important aspects of sustainable management of geothermal resources. Reinjection tests were started as early as 1974 in Beijing. Reinjection of return water form geothermal heating systems has been applied in Tianjin since 1996 and in Beijing since 2001. The reinjection experiences show that it is significant in lowering the reservoir pressure, and improving the heat mining of the geothermal field. In the Xiaotangshan area in Beijing, the reinjection volume has reached about 60% of the geothermal water production. As a result, the water level of the geothermal field has stopped declining. This is a very good example of sustainable use of geothermal resources. It is proposed that reinjection be expanded in Beijing and Tianjin, as well as other geothermal fields in the world. However, reinjection is one of the most complicated technique of reservoir engineering, and pre-mature thermal break through should be avoided by the application of tracer tests and proper monitoring.

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