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Reinjection of cooled water into sandstone geothermal reservoirs in China: a review

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ABSTRACT: Low injectivity of sandstone geothermal reservoirs during reinjection of geothermal waste water is a problem generally encountered in China, and has become a main obstacle for sustainable development of the geothermal resources. Over the last few decades, researchers have made much efforts to solve it based on the studies of reinjection schemes, hydrogeology of the reservoirs, well completion, reinjection water disposal techniques, and water-rock interactions focused on precipitation/dissolution reactions during reinjection. These studies have been very helpful in improving the injectivity. However, there are still many problems remaining for further investigations, among which characterization of the complete process of water-rock interactions during reinjection with the change in redox conditions, CO_2 partial pressure, non-isothermal transport process of the reinjection water, and the mechanism of release, transport and sedimentation of colloidal particles on reservoir permeability being taken into account are considered to be the most necessary. This paper gives a brief review of the history and state of the art of the research works on reinjection of cooled water into sandstone geothermal reservoirs, and outlooks the research demands in water-rock interactions during reinjection in the future.

Key words: reinjection, sandstone, geothermal reservoirs, injectivity, water-rock interaction

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1. INTRODUCTION

Geothermal resources can provide stable, continuous and high efficient energy, and is believed to play an important role in future energy structure and in improving the recently emerged air pollution in China (Wang, 2015a). China is abundant in low to medium temperature geothermal resources, which amount to 2.21×10^{12} TCE (Ton of Standard Coal Equivalent), in which the available thermal water is 3.72×10^{11} m^3/y (Wang, 2015b). China has taken the first place in direct use of geothermal resources in the world for more than twenty years. Hydrothermal resources is the main type of geothermal resources being exploited compared with Hot Dry Rock/Enhanced Geothermal System and shallow geothermal resources for the time being. These resources are mainly located in large sedimentary basins across central and eastern China, such as the Bohai Bay Basin, South Huabei Basin, Subei Basin, Songliao Basin, Guanzhong Basin, Jianghan Basin, Ordos Basin and Sichuan Basin (Fig. 1). The lithology of the reservoir rocks is mainly of two types, i.e., carbonates and sandstones. Most of the sandstone formations are of the Cenozoic (except for that of the Songliao Basin, Ordos Basin and Sichuan Basin, which are mainly of the Mesozoic and Permian), while the carbonate formations are of the Pre-Cenozoic, and thus the carbonate reservoirs usually underlie the sandstone reservoirs. As the buried depth of the carbonate reservoirs are usually very large (e.g., 900–9000 m in the Huanghua Depression, Bohai Bay Basin), they are generally exploited in areas where the bedrock is uplifted, such as in the Changxian Uplift and Niutuozhen Uplift in the Bohai Bay Basin and the Jianhu Uplift in the Subei Basin (Chen et al., 1994; Yang, 2011). In contrast, as sandstone reservoirs are characterized of a large thickness, widespread distribution and an appropriate buried depth (ca. 800–3000 m for easy survey and economical drilling), they

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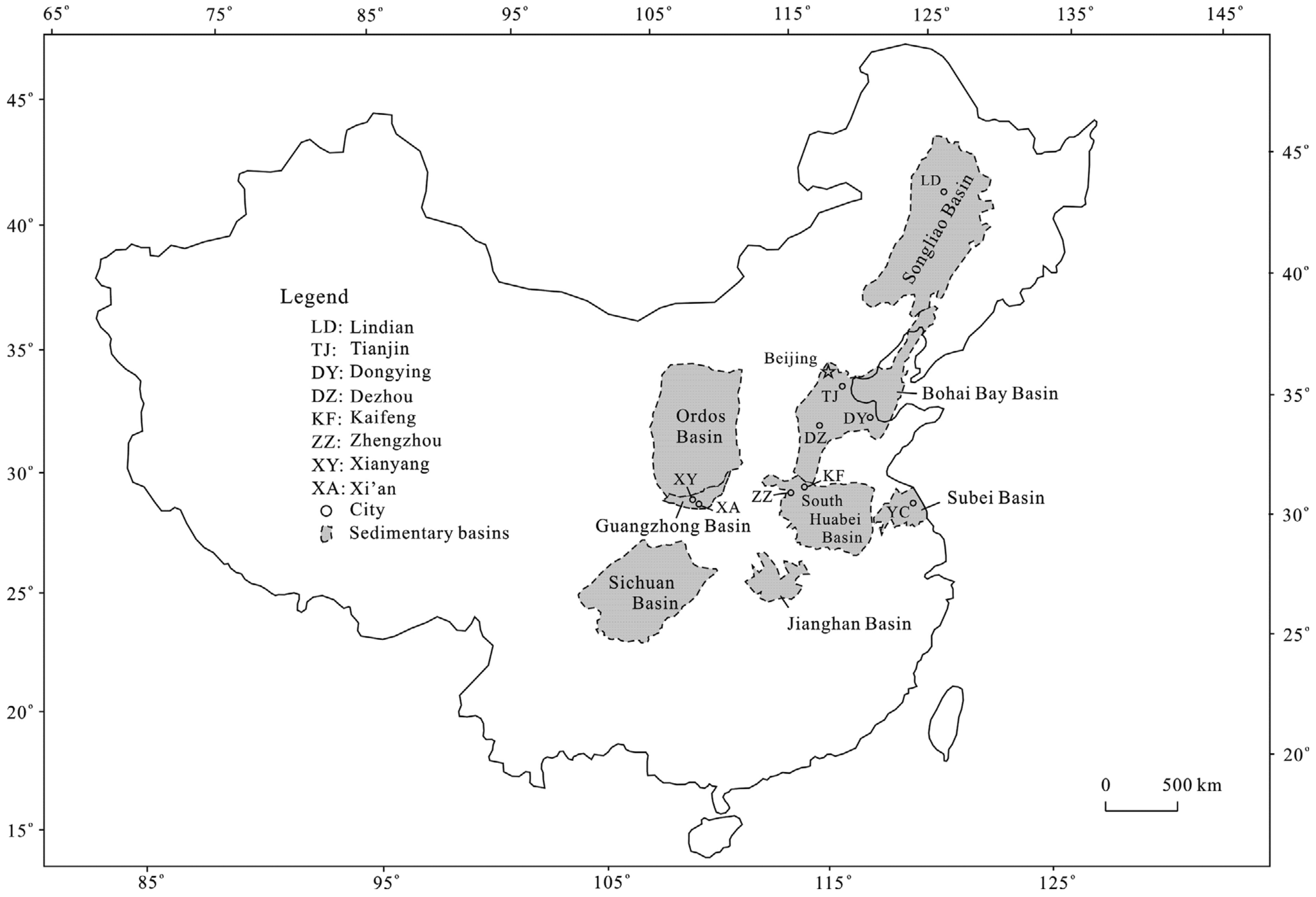

Fig. 1. Main sedimentary basins with sandstone geothermal reservoirs in China.

have been exploited widely throughout the country.

Nowadays, doublets has been widely applied in the development of hydrothermal resources. In the operation, geothermal fluids are pumped out from the production well and transferred through a heat exchanger to a district heating network where the heat content is utilized and the cooled water is reinjected into the reservoir by a reinjection well at a sufficient distance from the production well. Reinjection of geothermal waste water has been identified as an effective way in maintaining the pressure of geothermal reservoirs (Rybach, 2003), and has been applied successfully in many countries, such as in America, Costa Rica, French, Germany, New Zealand, etc. (Stefánsson, 1997). However, reinjection in carbonate and sandstone reservoirs are quite different. As the carbonate formations being exploited in the Bohai Bay Basin had gone through erosion and leaching due to regional uplift in the Middle Ordovician–Early Carboniferous and Mesozoic–Paleogene, accompanying with intense tectonic activities, they are characterized of highly developed karst and fracture-dominated secondary permeability (Zhai, 1997), thus reinjection in carbonate reservoirs are easy, with a reinjection rate usually above 80% and can even reach up to 100% in some cases (Zhao et al., 2014). But for the sandstone reservoirs, reinjection is more difficult, resulting in a very low reinjection rate (Zhao et al., 2014). This has become a main obstacle towards sustainable development of the geothermal resources. A lot of research works focused on reinjection of cooled water into sandstone geothermal reservoirs have been carried out in China, and have played an important role in improving the injectivity of the sandstone reservoirs. This paper intends to give a brief review of the research works on the mechanisms of the low well injectivity during reinjection and the technologies aiming to improve reinjection performance of the sandstone reservoirs in China, as well as a prospect of the research demands in the next step.

2. GEOTHERMAL FIELDS

As the rocks are in the early diagenesis stage, the porosity type of the Cenozoic formations is different from that of the Mesozoic formations, i.e., the porosity of the sandstone reservoirs is located within the intact-rock in the Cenozoic formations and within the fracture in the Mesozoic and Permian formations (Chen et al., 1994). Thus, the permeability of the Cenozoic reservoirs are usually much higher than that of the Mesozoic

Table 1. Characteristics of main sandstone geothermal reservoirs in China

Basin	Geothermal fields	Reservoirs	Porosity (%)	Permeability (10^{-3} μm^2)	Water type	TDS (g/L)	Reservoir temperature (°C)
Bohai Bay	Tianjin	N	25–38	15–7500	HCO_3-Na, HCO_3·Cl-Na	0.5–1.0	37–80
	Dongying	N	30–36	800–1400	Cl-Na	17.8–20.0	53–55
		E	28–30	900–1200	Cl-Na·Ca	2.0	65–70
	Dezhou	N	24–30	800–1400	Cl-Na	4.0–5.0	50–58
South Huabei	Kaifeng	N	25–35	nd	HCO_3-Na	0.7–4.6	33–60
	Zhengzhou	N	25–35	nd	HCO_3-Na, HCO_3-Ca·Na	0.8–1.0	32–44
Subei	Yancheng	N	23–38	200–1100	Cl·HCO_3-Na, HCO_3·Cl-Na	0.6–1.4	42–55
Guanzhong	Xianyang	N	9–35	16–13600	Cl-Na, Cl·HCO_3-Na	1.3–8.0	53–106
	Xi'an	N	4–37	16–13600	HCO_3·SO_4-Na, SO_4·HCO_3-Na, Cl-Na	0.7–8.3	55–102
Jianghan		E	nd	nd	Cl-Na	120–330	45–110
Songliao	Lindian	K	23	280	HCO_3·Cl-Na	1.3–9.4	46–85
Ordos		K, J, T, P	5–28	0.01–386	SO_4-Na·Ca, Cl·SO_4-Na, Cl-Na, Cl-Ca	0.5–31	22–70
Sichuan		J, T	2–22	0.2–16	HCO_3-Ca, Cl-Na, Cl-Na·Ca	1–50	20–80

and Permian reservoirs (Chen et al., 1994). This is especially the case for the Neogene reservoirs. As the rocks are semi-consolidated, the porosity and permeability of these reservoirs can be rather high. In fact, they're the main reservoirs being exploited at present (Zhao et al., 2014) (Table 1). Generally, the porosity is 4–38% for the Cenozoic reservoirs (Chen et al., 1994; Zhu et al., 2003; Liang et al., 2008; Gao et al., 2009; Wang, 2010; Zhao, 2013), while it is 2–28% for the Mesozoic and Permian reservoirs (Chen et al., 1994; Yang, 2004; Wang, 2007; Yuan, 2007; Xie et al., 2008; Tong et al., 2011; Liang et al., 2012; Wan, 2012; Li, 2013) . The permeability is 15–13600 × 10^{-15} m^2 and 0.01–280 × 10^{-15} m^2 for the Cenozoic and the Mesozoic and Permian reservoirs, respectively (Chen et al., 1994; Zhu et al., 2003; Yang, 2004; Wang, 2007; Yuan, 2007; Liang et al., 2008; Xie et al., 2008; Gao et al., 2009; Tong et al., 2011; Liang et al., 2012; Wan, 2012; Li, 2013; Zhao, 2013; Du et al., 2016). The permeability of the reservoirs in Tianjin and Xianyang is the highest, which reaches up to 7.5 × 10^{-12} m^2 and 13.6 × 10^{-12} m^2, respectively (Chen et al., 1994; Liang et al., 2008). These sandstone reservoirs all belong to low to medium temperature geothermal systems. The well head temperature of the thermal waters are 20–102 °C (Chen et al., 1994). The TDS (Total Dissolved Solids)of the thermal waters from the Cenozoic reservoirs are lower than 8.0 g/L (Chen et al., 1994; Cheng, 2007; Lin et al., 2007; Zhou et al., 2007; Huang, 2010; Tan, 2010; Yang, 2011), except for that in Dongying which reaches up to 17.8–20.0 g/L, with water types mainly of HCO_3-Na, Cl·HCO_3-Na and Cl-Na (Gao et al., 2009), while the TDS of the Mesozoic and Permian reservoirs are higher, which reaches up to 0.50–50.0 g/L (Chen et al., 1994; Hou, 2008; Liang et al., 2012).

Up to now, all the sandstone reservoirs have undergone exploration and development to some extent. In the Songliao Basin (Zhu, 2011a), Ordos Basin (Yin et al., 2008), Sichuan Basin (Luo et al., 2016) and Jianghan Basin (Li et al., 2016), primary exploration works have been carried out but with no large scale development, except for Lindian in the Songliao Basin, where the geothermal resources have been exploited for district heating since 1997 (Tong et al., 2011). In the other basins, thermal water have been exploited concentratedly in several geothermal fields, such as Tianjin, Dongying and Dezhou in the Bohai Bay Basin (Gao et al., 2009; Zhao, 2013; Zhao et al., 2014), Kaifeng and Zhengzhou in the South Huabei Basin (Lin et al., 2007; Huang, 2010), Yancheng in the Subei Basin (Yang, 2011), and Xianyang and Xi'an in the Guanzhong Basin (Liang et al., 2008). However, not all the geothermal fields have deployed large scale reinjection except for Tianjin (Zhao et al., 2014). In the other geothermal fields, only field experiments on reinjection have been carried out (Liang et al., 2008; Tan, 2010; Wang, 2010; Tong et al., 2011; Yang, 2011; Zhu, 2011b; Zhao, 2013). Due to lack of reinjection or low injectivity, the water head in these geothermal fields declines fast (Zhao et al., 2014). Taken the Neogene Guantao Formation (N_g) in Tianjin which has the longest development history, largest exploitation amount and highest study level of reinjection as an example, the reinjection rates for individual geothermal doublet are lower than 20% at present, resulting in continuous decrease of the reservoir pressure since 1970s, which reached up to 5 m/year in 2013 with a buried depth of the water head of 82–110 m (Wang, 2014). The mechanism accounts for the low injectivity of the sandstone reservoirs includes many aspects, such as reinjection schemes, hydrogeology of the reservoirs, well completion techniques, physical and chemical clogging of the reinjection wells, and water-rock interactions between the reinjected water and the reservoirs (Ungemach, 2003; Liu and Zhu, 2009). In china, a lot of researches have been carried out on reinjection schemes, well completion and water disposal techniques.

3. RESEARCHES ON REINJECTION: HISTORY AND STATE OF THE ART

3.1. Reinjection Schemes

The first research works on geothermal reinjection have been carried out in Tianjin since 1980s (Lin et al., 2008), followed by several cities such as Dezhou, Dongying, Xi'an and Xianyang after 2000 (Zhou, 2007; Tan, 2010; Chen, 2012; Yun, 2014). These works are focused on reinjection schemes of the Neogene sandstone reservoirs, including the modeling of thermal breakthrough (Cheng et al., 2011), field experiments exploring into the effect of water temperature and injection pressure on well injectivity (Wang, 2014), and modeling of the evolution of temperature and pressure field of the reservoirs under pumping and reinjection (Lei and Zhu, 2013), etc. The main findings are i) the injection rate is positively correlated with the temperature of the injected water, which is ascribed to lower viscosity of the injected water under higher temperatures (Fig. 2a) (Zhou et al., 2007; Wang, 2014), ii) the injection rate through the well tube is higher than that through the pump tube, which is ascribed to the higher resistance for the injected water through the pump tube since there is a pump installed at the tube end (Fig. 2b) (Lin et al., 2006), iii) the injection rate under pressure is higher than that merely under gravity, e.g., Lin et al. (2008) found that the injection rate is proportional to the pressure applied for N_g in Tianjin. Zhou et al. (2007) found that the injection rate increases with the pressure applied but varies by a power function (Fig. 2c) and the injectivity decreases under higher pressures (Fig. 2d) for N_g in Dezhou, and iv) reinjection of cooled water into the low to medium temperature sandstone reservoirs is practicable by a doublet with suitable separation, e.g., Chen (2012) conducted a tracer test for the Neogene Bahe-Lantian ($N_{bh\text{-}l}$) sandstone reservoir in Xi'an, finding that the tracer injected into the reinjection well arrived at the pumping well 220 m away within 42 d, with no significant temperature decrease in the product water. Lei and Zhu (2013) proposed that the distance between the injection and production wells should be greater than 500 m to avoid thermal breakthrough based on numerical modeling of various exploitation and reinjection schemes for N_g in Tianjin.

3.2. Hydrogeology

Characteristics of hydrogeology, especially the permeability and transmissivity of the sandstone reservoirs affects well injectivity. Lin and Zhao (2010) suggested that for N_g deposited in sedimentary environment of main or tributary river channels with a thickness

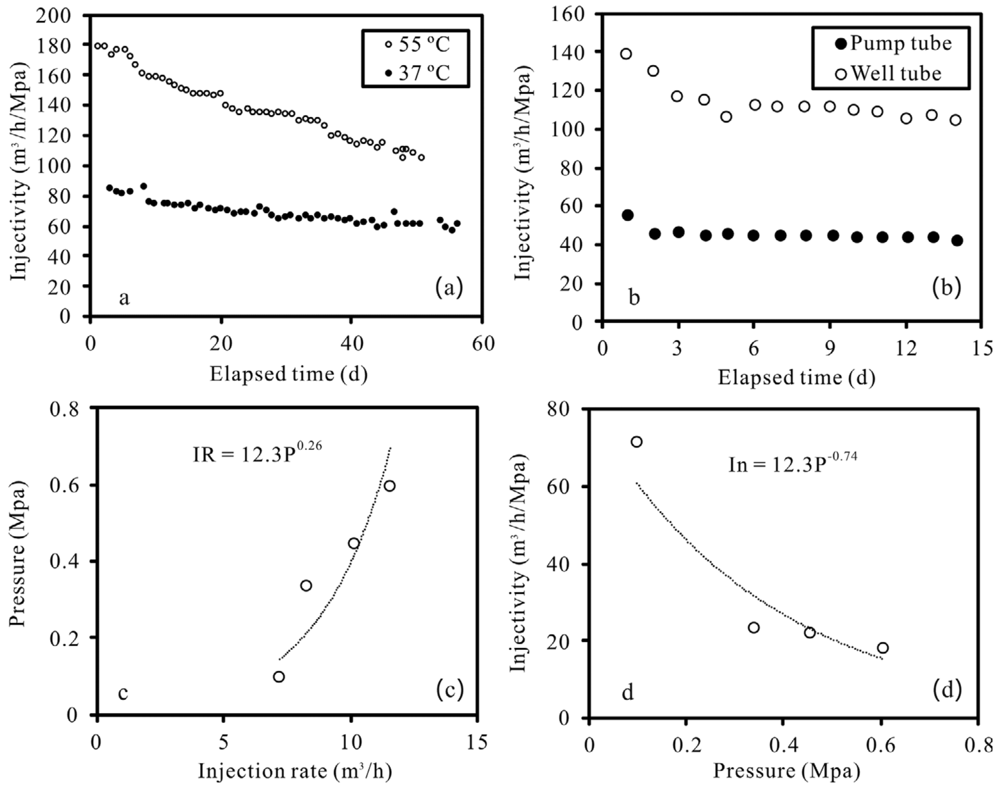

Fig. 2. Well injectivity for various reinjection schemes. (a) Reinjection with water of various temperatures; (b) Injection through pump tube and well tube; (c) Injection rate under various pressures, IR: injection rate, P: pressure; (d) Injectivity under various pressures, IR: injectivity, P: pressure (Zhou et al., 2007; Wang, 2014).

of more than 10 m for individual layers and a total thickness of more than 50 m, permeability above 1×10^{-12} m^2, porosity above 30% and clay content below 15% is most favorable for reinjection. It has been identified by the reinjection experiment of well T38-1 in Tianjin, where N_g is of braided river facies, with a porosity of 31–35%, clay content of 15–23%, permeability of $0.85–1.44 \times 10^{-12}$ m^2, thickness of 8–12 m for individual layers and 82.7 m in total (Dong et al., 2016). The injection rate reaches up to 51 m^3/h and the water reinjected accounts for 98% of the water exploited. Gao et al. (2009) classified N_g and Paleogene Dongying (E_d) sandstone reservoir into several zones with different reinjection performance based on nemerow index method, taking porosity, permeability, thickness, groundwater head, complexity of geologic structure and content of dissolved gas of the reservoir fluid into account. It can be very useful for site selection with respect to reinjection.

3.3. Well Completion

Different well completion techniques have been studied with respect to different geologic conditions of the reservoirs. Primarily, "Monolayer Screen", which is a type of screen made by winding a layer of rolled wire around a perforated steel pipe, is widely applied in well completion for the Neogene reservoirs in Tianjin. However, the injection rate is as low as 20 m^3/h in gravitational reinjection, and no more than 31 m^3/h in pressured reinjection due to clogging by suspensions (Zhao, 2014). In order to solve this problem, "Double Layer Screen" was designed based on laboratory experiments in 2002, which is made by a double layer screen of different size of screen openings with silica sand placed between the two screens (Zhao, 2014). It was believed that the screen is applicable to reservoirs with a large buried depth and when the lithology of the rock is of silt and fine sandstones which is not suitable for gravel-filled screen. However, field tests indicated that the water-resistance was too high, resulting in an injectivity even lower. Although the parameters such as the diameter, porosity and thickness of the filled quartz sand for the screen were improved, still the well injectivity couldn't be improved significantly. Thus another method based on "Monolayer Screen" was proposed by applying "Gravel-packed Completion Technique". The technique not only uses a monolayer screen in well completion, but also fills a layer of silica gravel around the screen. The gravel filled is 2–4 mm in diameter, more than 75 mm in thickness and covers the whole length of the screen to effectively filter the water and stop the sand from flowing into the well. This type of well screen has a good performance in improving well injectivity. Recently, perforation has been used in well completion (Dong et al., 2016). The technique uses a gun perforator to penetrate well casing and cement sheath to enhance reservoir permeability and enlarge water-collection area. It is very effective in improving well injectivity for formations that are characteristic of high porosity, good cementation and low clay content. In the reinjection experiment carried out in Donggu and Binhai in Tianjin, the injection rate reaches up to 64 and 102 m^3/d, respectively (Table 2) (Wang, 2014; Zhao, 2014).

3.4. Water Disposal

Suspensions in reinjection water may result in clogging of the well or formation. The sources of suspensions include i) small mineral particles in the product water. It is reported that by filtration of the product water and reinjection water with 0.45 μm membrane for the Neogene reservoirs in Tianjin, mineral particles including plagioclases, quartz, K-feldspar, Mg and Fe silicates, pyrite and Fe and Zn oxides were observed (Gao and Zeng, 2007), among which the oxides of Fe and Zn were identified as the product of oxidation of the steel water delivery pipelines (Minissale et al., 2008), ii) precipitation of minerals due to lower pressure and temperature of the reinjection water compared with the formation water, which may result in degas of CO_2 and increase in pH, favoring precipitation of carbonite such as aragonite, calcite, dolomite and magnesite, or result in lower solubility and supersaturation of some minerals such as barite (Pang et al., 2011). To treat the suspensions, steel pipelines for water delivery have been changed into plastic ones, and a two-level filtration system equipped with 50 μm and 1–5 μm membranes, which can filter out most of the suspensions

Table 2. Performance for different well completion techniques in Tianjin

Reinjection Well	Lithology	Porosity (%)	Permeability (10^{-3} μm^2)	Well depth (m)	Well completion	Length of screen (m)	Temperature of injected water (°C)	Injection flow rate (m^3/h)
Dagang	siltstone with gravel	29.9	500–600	1900	MS	58.6	32–55	15–20
Tanggu	sandstone and conglomerate	20.0	740–1270	2025	MS	61	25–30	20–50
Wuqing	sandstone	20.1–31.6	170–870	2347	DLS	93.9	47–52	21–49
Dongli	sandstone and conglomerate	24.0–32.0	420–1080	1362	LDGF	95.1	19–48	30–66
Donggu	sandstone and conglomerate	26.0–31.0	450–950	1950	P	75.2	31	64
Binhai	sandstone	24.0–32.0	350–940	2105	P	90	18–36	102

Note: MS, monolayer screen; DLS, double layer screen; LDGF, large diameter gravel-fill; P, perforation.

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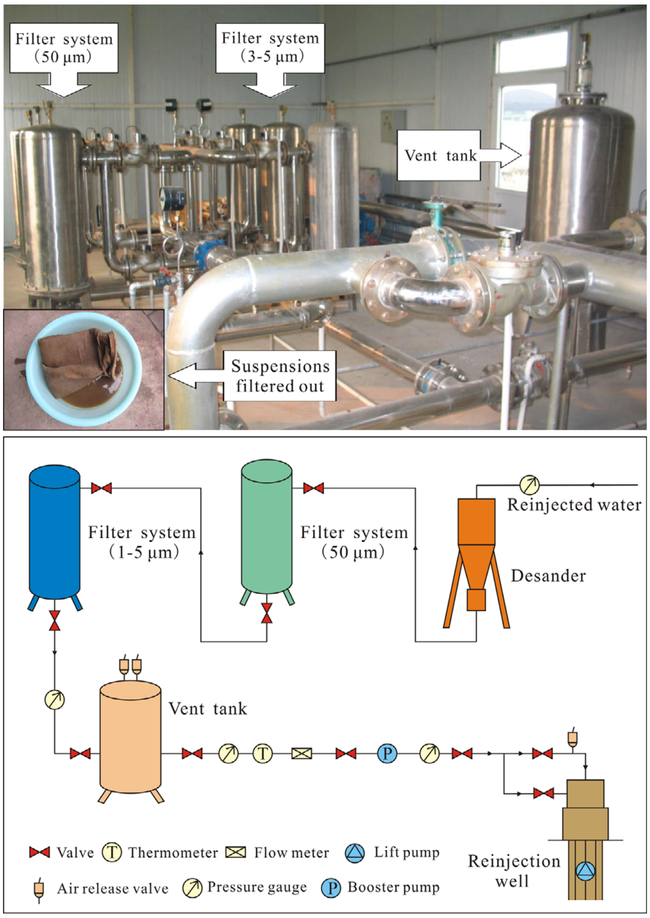

Fig. 3. Two-level filtration system for disposal of reinjection water in Tianjin.

has widely been applied (Fig. 3). Furthermore, gas may release due to decrease in pressure during water delivery in the pipelines or be brought into the reservoir when the reinjection well has a fault in air tightness, and can also result in well or formation clogging, especially when the reinjection rate is low (Yuhara and Maruyama, 1996). This has been treated by adding a degas tank at the reinjection well head, which can remove most of the excess gas in the reinjection water and by keeping air tightness of the reinjection well. The technique for water disposal focus on prevention of suspension clogging and gas clogging has been applied widely in Tianjin. In the technical procedure, the reinjection water firstly flows through a desander to remove the large particle suspensions, and then flows through the two-level membrane filtration system to remove the small particle suspensions. Excess gas in the reinjection water is released by flow through a vent tank (Wang, 2014). A standard for application of the technique has been proposed and popularized in Tianjin since 2006 (TGEDDI, 2006).

Microbes is another factor which can result in clogging. Sulfate-reducing bacteria, iron bacteria and saprophyte are the microbes discovered most frequently (Gao and Zeng, 2007). Reproduction of these microbes can be very fast under suitable conditions, forming biofilms around the reinjection well and causing clogging of the well or formation, e.g., a core flooding experiment with reinjection water containing iron bacteria and saprophyte for the N_{bh-1} in Xianyang shows that the permeability of the core reduced by 15.3%, while it was only 4.1% for the case in which the reinjection water was sterilized (Yun, 2014). Clogging by microbes is easy to handle by sterilization of the reinjection water and reinjection well with microbicides. To avoid microbial clogging, it is suggested that the number of sulfate-reducing bacteria should be less than 10 cells/mL while iron bacteria should be less than the order of magnitude of 10^4 cells/mL in the reinjection water (Gao and Zeng, 2007).

3.5. Water-Rock Interactions

Changes in chemical composition and redox conditions of the reinjection water may induce a series of water-rock interactions between the reservoir rock and fluids and the reinjected water which may have an impact on reservoir porosity and permeability (Ungemach, 2003). These changes may be caused by the following two reasons. One is decrease in temperature and degas of CO_2 which can result in changes of composition of the reinjection water (Pang and Reed, 1998), and subsequently, after entering the reservoir, the reservoir temperature near the reinjection well will decrease (Cheng et al., 2011). These changes may result in precipitation of secondary clay and hydrothermal minerals, such as montmorillonite, chalcedony, calcite and other minerals with high reaction rates (Chen, 1998; Dou, 2012; Li et al., 2012). The other reason is air introduction into reservoirs, which can be the result of poor sealing of reinjection wells or water delivery pipelines. This may lead to increase in dissolved oxygen and initiate redox reactions. For instance, when reservoirs contain pyrite, the dissolution of Fe and the subsequent precipitation of $Fe(OH)_3$, goethite, siderite and other minerals may be promoted, resulting in changes in ionic composition and pH of the water. These changes may induce a series of dissolution/precipitation reactions and affect the permeability of the reservoir (Xu et al., 2003). Both modeling and laboratory experiments have been conducted, e.g., Pang and Reed (1998) proposed a method for correcting the error in the analysis of Al and degassing of CO_2. Chen (1998) carried out a thermodynamic modeling investigating into the secondary mineral assemblages of the water-rock interactions during reinjection and the impact on porosity of N_g in Tianjin, concluding that the porosity of the reservoir may increase slightly, which is ascribed to the dissolution of some of the aluminosilicates minerals such as feldspars in the reservoir around the reinjection well which are unsaturated with respect to the reinjected water. Zhou (2013) studied the effects of water-rock interactions on reservoir permeability during reinjection for the Xi'an geothermal field based on core flooding experiments and thermodynamic simulation, finding that the oxidation of Fe^{2+} to Fe^{3+} aggregates clogging of the core.

Physical aspects of the water-rock interactions may also reduce well injectivity. Since transport of the reinjected water is non-isothermal, decrease in temperature can result in higher viscosity of the reinjected water, and increase in temperature at the forefront of the reinjected water plume can cause expansion of the water, generating resistance to the water flow behind the forefront. Based on analysis of the characteristics of the time series of the well injectivity during reinjection of N_g, it is concluded that non-isothermal transport of the reinjected water may have a major impact on reservoir permeability (Lin and Zhao, 2010).

4. RESEARCH DEMANDS

The current researches have covered the main mechanisms affecting well injectivity, i.e., the reinjection scheme, hydrological characteristics of the reservoir, quality of reinjected water, well completion methods and water-rock interactions between reinjected water and reservoir. However, the complete process of the water-rock interactions and the impact on reservoir permeability has not yet been fully elucidated. Furture research demands may include i) the evolution of reservoir temperature and pressure fields during non-isothermal migration of the reinjected water, and its impact on reservoir permeability and well injectivity, which can be done by non-isothermal modeling coupled with laboratory experiments. For example Jeanne et al. (2015), in a case of injection of cool water with a hot reservoir showed that permeability gain mostly occurs around the injection well due to thermal contraction of the rock. ii) characterization of the complete process of water-rock interactions during reinjection taking into account of the change in redox conditions, CO_2 partial pressure and THC (thermo-hydrodynamic-chemical) coupling process, and evaluation its impact on reservoir permeability, and iii) characterization of the release, transport and sedimentation of colloidal particles (1 nm–1 μm) on reservoir permeability which has not been given enough concern with respect to geothermal reinjection.

5. CONCLUSIONS

Research works on reinjection of cooled water into sandstone geothermal reservoirs in China have been focused on reinjection schemes, hydrogeology of the reservoirs, well completion, water disposal techniques and some chemical and physical aspects of water-rock interactions between reinjected water and reservoir. The techniques of well completion and water disposal have been improved a lot and shown a good performance now. However, the low injectivity of sandstone reservoirs are still not completely resolved. Further researches mainly on the mechanism of water-rock interactions during reinjection are still needed, including the non-isothermal migration of reinjection water, the THC process of water-rock reactions and the release, transport and sedimentation of colloidal particles in the reservoir, and their impact on reservoir permeability and well injectivity.

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