Water quality deterioration of treated oilfield injection water in the water distribution system of the Jianghan oilfield

Ji Li, Yaru Wang, Shenglan Li, Liping Fang, Guangcheng Hou and Baoyou Shi

ABSTRACT

The deterioration of treated oilfield injection water quality in the distribution system has become a common issue that hinders the application of oilfield wastewater as a reusable source for oil production. Hereby, this work devotes to monitoring treated water parameters and the formation of pipe scales in the whole distribution system in Jianghan oilfield. Our results showed that the cause of water deterioration in the distribution system is due to the increased suspended solids. Coupon tests indicated that the rates of pipe corrosion and scale formation significantly increased, which was in line with our monitoring data. This further demonstrates that the deterioration of injection water leads to significant pipe corrosion and scale formation after the long distance transportation from effluent wastewater treatment plants to injection wells. The chemical composition of the collected pipe scale is consistent with that of suspended solids extracted from water samples. This indicates that the increased suspended solids in water are likely due to the contribution of pipe scale that can be on the walls of pipelines, consequently deteriorating the injection water quality. The findings of the present study show an important significance in understanding the mechanism of injection water deterioration in the distribution system.

Key words | iron corrosion, oilfield, pipe scale, wastewater treatment, water deterioration

INTRODUCTION

Water injection into oil reservoirs is an important process during oil exploitation, which has been widely adopted to provide constant pressures, and hence enhancing oil yield in oilfield operation nowadays (Sanyal et al. 2017). However, this process also causes the excessive production of wastewaters due to the high yield of concomitant wastewater during the oil recovery process (Yousef et al. 2011; Chen et al. 2012). The generated wastewater generously contains complicated chemicals, residual oil and suspended particles, which cannot be directly introduced into the environment (Utvik 2001; Li et al. 2006; Zhao et al. 2006). Hence, the proper treatment of wastewaters is of great importance with respect to both economic and environmental concerns. In recent years, the reinjection of the treated wastewater into oil reservoirs has become a popular solution to reuse the precious water resource, and minimize the adverse impact on ecosystems (Hou 2007; Ji et al. 2012; Fang et al. 2017), especially at those offshore oilfields in China. Meanwhile, the treatment cost of the generated wastewater is significantly reduced for the purpose of reinjection due to the fact that much fewer water parameters such as total suspended solids (TSS) and oil content are considered according to the Chinese reinjection water standard for petroleum and natural gas fields. As one of the largest oilfields
in the middle of China, Jianghan oilfield has over 100 water treatment plants (WTPs) delivering treated reinjection water to thousands of injection wells, subsequently ensuring a constant annual oil yield for the oil company. In general, there are mainly four processes to treat the generated wastewaters before delivering them to individual oil wells through the water distribution system; namely, residual oil recovery, chemical coagulation and sedimentation, disinfection (bacteria inhibition) and filtration (Campos et al. 2002; Tellez et al. 2002; Xu & Zhu 2004; Ahmadun Fakhru L-Razi 2009; Liu et al. 2009; Carpenter 2014).

Nevertheless, evidence already shows that the treated wastewaters frequently suffer from the problem of water deterioration in the distribution system, subsequently resulting in clogging injection wells and affecting oil production (Zhao et al. 2005; Cui et al. 2012). Only a few studies have previously addressed this problem by far, while controversial findings are usually found in the literature. Liu and coworkers predicted the formation of pipe scale in Daqing oilfield, and suggested that the accumulation of scale is the major cause of water deterioration from the effluent of WTP to injection wells (Liu et al. 2009), whereas, a parallel study ascribed the reason of the reinjection water deterioration to the corrosion of the pipeline in the Daqing oilfield (Dong et al. 2015). Both studies have shown that the water quality of effluent from WTPs is essentially critical to water deterioration. Differing from industrial wastewater, the salinity of the treated reinjection water can be up to several hundred grams per liter, containing high contents of calcium, magnesium, chloride and sulfate (Alkhudhiri et al. 2013; Sharghi et al. 2015). However, very few studies explore the importance of those water parameters to the deterioration of reinjection water. Meanwhile, previous findings on scale formation and pipeline corrosion were mainly based on laboratory-scale study under simulated conditions, which is probably not able to reflect the actual mechanisms of water deterioration in the distribution system. There is a lack of direct evidence of water quality with scale formation and corrosion of water pipelines. Moreover, the water quality is highly related to the local geological conditions. To our best knowledge, relevant study in the Jianghan oilfield is still scarce.

This study aims to systematically evaluate variation of several key water parameters such as pH, various cations and anions, salinity and TSS from effluents of the two WTPs to injection wells in Jianghan oilfield. Meanwhile, combining an in-situ scale formation and pipeline corrosion study and the physicochemical properties of TSS from different sites, the mechanisms of the injection water deterioration are further addressed.

**MATERIALS AND METHODS**

**Study sites and sample collection**

The study area is located at the Jianghan oilfield, Qianjiang, where the location is in the middle of China (Figure S1(a)). The reinjection water was treated within an oil wastewater treatment plant (WTP) (Figure S1(b)), prior to distribution to different injection oil wells through the respective transfer station (TS). The reinjection water samples were taken from the effluent of the WTP in Jianghan oilfield, four different TSS (TS #1, #2, #3 and #4) and the selected oil wells (oil well #1, #2, #3, and #4) corresponding to each TS of the water distribution system (Figure S1(c)). After that, the water samples were immediately transported to our laboratory, and stored at 4 °C in a refrigerator before further use in this study. (Figure S1 is available with the online version of this paper.)

**Water quality analysis**

The concentrations of TSS in the samples were measured by filtrating water samples using a 0.45 μm membrane, and then weighing the filtered particles on a digital balance. Particle size of TSS was measured by a Mastersizer 3000 laser particle size analyzer (Malvern, UK). Total dissolved solids (TDS) was determined using a TDS meter (H198129, Hanna instruments, Italy) after a proper dilution.

The iron (II) (Fe(II)) content was determined by using a modified phenanthroline method. The total Fe was determined after the reduction of Fe(III) to Fe(II) using 10% hydroxylamine hydrochloride as a reductant. The sulfide content in the water samples was determined using a UV/vis spectrophotometer (Persee TU1901, China) after reacting with N,N-dimethyl-p-phenylene diamine. The oil content was also determined at a wavelength of 250 nm on UV/vis spectrophotometer after extraction from samples using petroleum ether. The concentrations of calcium (Ca)

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### Footnotes

1. Alkhudhiri et al. (2013).
and magnesium (Mg) were measured on an Optima 7000 inductively coupled plasma optical emission spectrometer (ICP-OES; Perkin Elmer, USA), while the concentration of bicarbonate (HCO$_3^-$) was quantified via titration of samples with hydrochloric acid (HCl). Viable counts of sulfate reducing bacteria (SRB), ferric bacteria (FB) and saprophytic bacteria (TGB) were determined with the ‘most probable number’ method.

Solid sample characterization

The chemical compositions of TSS particles and pipe scales collected from the reinjection water distribution system were analyzed by ICP-OES. The crystalline structures of the collected suspended solid samples from the effluent of the WTP and the injection well waters were characterized on an X’Pert PRO MRD diffractometer (PANalytical, The Netherlands) applying monochromatic Cu Ka radiation (\(\lambda = 0.15405 \text{ nm}\)) with a scanning rate of 5 degree/min.

In-situ scale formation and corrosion tests

To examine the effect of water quality on pipelines, in-situ coupon experiments on scale formation and pipeline corrosion were conducted according to a standard coupon protocol (Ailor 1971). In brief, a carbon steel coupon for the corrosion test and a titanium steel coupon for the scale formation test were installed on a coupon holder within the pipeline of both the WTP effluent and TS #1 respectively. The coupons were retrieved after 30 days, and the weight of the coupons was recorded and compared with their respective original weights. The corrosion (\(F\)) and scale formation (\(\delta\)) rates were calculated based on the following equations (Equations (1) and (2)).

\[
F = \frac{3650(m_1 - m_0)}{S \times T \times \rho}
\]

\[
\delta = \frac{(m_0 - m_1) \times 8760}{(2.65+S \times T)}
\]

where \(m_0\) (g) and \(m_1\) (g) represent the coupon mass before and after the experiment. \(S\) is the surface area of the coupon (cm$^2$), and \(T\) (d) and \(\rho\) (g/cm$^3$) refers to the experiment time and density of the coupon, respectively. The average density of the formed scale is 2.65 g/cm$^3$.

RESULTS AND DISCUSSION

Characteristics and variation of reinjection water quality in distribution system

The characteristics of the treated reinjection water quality in the distribution system (i.e. from the effluent of the WTP to different oil wells) have been given in Table 1. The results show that the TDS of treated injection water range from 215.9 to 240.8 g/L, and the pH values of the water samples

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>TSS* (mg/L)</th>
<th>Turbidity (NTU)</th>
<th>Particle size ((\mu)m)</th>
<th>pH</th>
<th>TDS* (g/L)</th>
<th>Oil content (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effluent of WTP</td>
<td>34 ± 1(^c)</td>
<td>29.6 ± 1.0</td>
<td>2.2 ± 0.8</td>
<td>6.9 ± 0.1</td>
<td>240.8 ± 8.3</td>
<td>15.3 ± 0.6</td>
</tr>
<tr>
<td>Transfer station #1</td>
<td>75 ± 4</td>
<td>35.5 ± 3.2</td>
<td>8.3 ± 1.0</td>
<td>6.9 ± 0.1</td>
<td>225.2 ± 5.2</td>
<td>15.4 ± 0.5</td>
</tr>
<tr>
<td>Transfer station #2</td>
<td>165 ± 15</td>
<td>136.3 ± 2.0</td>
<td>5.2 ± 1.3</td>
<td>6.8 ± 0.2</td>
<td>215.9 ± 9.1</td>
<td>14.8 ± 0.4</td>
</tr>
<tr>
<td>Transfer station #3</td>
<td>109 ± 13</td>
<td>83.4 ± 1.3</td>
<td>4.1 ± 1.5</td>
<td>7.0 ± 0.1</td>
<td>229.8 ± 6.5</td>
<td>12.1 ± 1.0</td>
</tr>
<tr>
<td>Transfer station #4</td>
<td>128 ± 19</td>
<td>155.0 ± 1.6</td>
<td>4.1 ± 0.9</td>
<td>6.8 ± 0.1</td>
<td>228.9 ± 4.5</td>
<td>11.6 ± 0.8</td>
</tr>
<tr>
<td>Oil well #1</td>
<td>121 ± 5</td>
<td>178.2 ± 2.3</td>
<td>9.7 ± 0.6</td>
<td>6.9 ± 0.1</td>
<td>245.2 ± 7.9</td>
<td>10.4 ± 1.0</td>
</tr>
<tr>
<td>Oil well #2</td>
<td>293 ± 6</td>
<td>573.0 ± 4.5</td>
<td>4.2 ± 1.2</td>
<td>6.9 ± 0.2</td>
<td>227.7 ± 8.1</td>
<td>12.5 ± 0.6</td>
</tr>
<tr>
<td>Oil well #3</td>
<td>105 ± 7</td>
<td>182.0 ± 6.1</td>
<td>4.4 ± 1.0</td>
<td>7.0 ± 0.1</td>
<td>228.8 ± 9.2</td>
<td>11.9 ± 0.9</td>
</tr>
<tr>
<td>Oil well #4</td>
<td>243 ± 8</td>
<td>366.0 ± 4.3</td>
<td>4.5 ± 0.9</td>
<td>6.8 ± 0.0</td>
<td>230.1 ± 7.2</td>
<td>12.7 ± 0.5</td>
</tr>
</tbody>
</table>

\(^{a}\)TSS, total suspended solids.  
\(^{b}\)TDS, total dissolved solids.  
\(^{c}\)Average ± standard deviation.
remain at around 7.0 constantly. Importantly, the concentration of TSS is 34 mg/L for the effluent of the WTP, and from 65 to 128 mg/L for the water samples from the transfer stations, and from 105 to 293 mg/L at the water injection wells, respectively, showing a tendency for a dramatic increase of TSS in the reinjection water during delivery. This is in line with the turbidity data showing a good correlation with TSS values ($R^2 = 0.8869$). Our results also show that the content of TSS significantly enhances with the increase in the delivery distance from the WTP (Figure S1(c)). The evidence clearly suggests that the occurrence of water quality deterioration is likely due to the increase of TSS content in the delivery process (Figure S1(c)), in agreement with the findings in the Liaohe oilfield reported by Dong and coworkers (Dong et al. 2013).

The concentrations of some major ions in the distribution system have been summarized in Table 2. The concentrations of Ca and HCO$_3^-$ are extremely high, which decrease from 1,350.6, 573.0 to 1,007.8, 378.4 mg/L, respectively, with the transport of treated waters. The difference between the WTP and oil well #4 were 342.8 and 194.6 mg/L. The concentrations of Mg are higher than 100.4 mg/L in the whole distribution system. The high concentrations of Ca and HCO$_3^-$ in rejection waters lead to a high probability of scale formation (Wu et al. 2010). The concentration of Fe(II) and total Fe is up to 13.6 and 19.4 mg/L, respectively, after a long distance transport, which is significantly higher than that (i.e. 1.7 mg/L) in the effluent of the WTP. It can be inferred that the enhanced iron content in oil well #4 is attributed to the corrosion of the pipeline. The above results show that with the increase of transport distance of reinjection waters, the rates of pipe scale formation and pipeline corrosion become more severe.

### Characterization of TSS and pipe scale in the distribution system

The relative ratios of three important elements (i.e. Ca, Mg and Fe) in the TSS samples from different sites have been analyzed as shown in Figure 1. The results indicate that

![Figure 1](https://iwaponline.com/ws/article-pdf/19/2/519/591968/ws019020519.pdf)

**Figure 1** | Relative contents of the three important cations for total suspended solids (TSS) samples from different sites.

### Table 2 | The concentration of several important ions in water samples from Jianghan oilfield

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>HCO$_3^-$ (mg/L)</th>
<th>Fe$^{2+}$ (mg/L)</th>
<th>Total Iron (mg/L)</th>
<th>Sulfide (mg/L)</th>
<th>Ca$^{2+}$ (mg/L)</th>
<th>Mg$^{2+}$ (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effluent of WTP</td>
<td>573.0 ± 12.4$^a$</td>
<td>ND$^b$</td>
<td>1.7 ± 0.1</td>
<td>0.70 ± 0.15</td>
<td>1,350.6 ± 11.8</td>
<td>100.4 ± 4.9</td>
</tr>
<tr>
<td>Transfer station #1</td>
<td>431.2 ± 11.0</td>
<td>ND</td>
<td>3.6 ± 0.2</td>
<td>0.30 ± 0.12</td>
<td>1,219.1 ± 20.9</td>
<td>152.0 ± 6.2</td>
</tr>
<tr>
<td>Transfer station #2</td>
<td>471.9 ± 14.5</td>
<td>0.6 ± 0.2</td>
<td>0.6 ± 0.1</td>
<td>0.30 ± 0.10</td>
<td>1,210.9 ± 21.1</td>
<td>112.9 ± 5.1</td>
</tr>
<tr>
<td>Transfer station #3</td>
<td>418.3 ± 12.6</td>
<td>1.2 ± 0.2</td>
<td>4.0 ± 0.2</td>
<td>ND</td>
<td>1,116.5 ± 19.8</td>
<td>123.2 ± 8.0</td>
</tr>
<tr>
<td>Transfer station #4</td>
<td>405.1 ± 20.4</td>
<td>4.9 ± 0.1</td>
<td>5.0 ± 0.1</td>
<td>ND</td>
<td>1,167.4 ± 21.8</td>
<td>115.0 ± 5.0</td>
</tr>
<tr>
<td>Oil well #1</td>
<td>399.2 ± 12.6</td>
<td>3.8 ± 0.1</td>
<td>4.7 ± 0.3</td>
<td>ND</td>
<td>1,202.9 ± 31.9</td>
<td>133.9 ± 6.2</td>
</tr>
<tr>
<td>Oil well #2</td>
<td>434.7 ± 10.6</td>
<td>3.6 ± 0.3</td>
<td>4.2 ± 0.1</td>
<td>ND</td>
<td>1,154.7 ± 30.0</td>
<td>125.6 ± 9.8</td>
</tr>
<tr>
<td>Oil well #3</td>
<td>389.2 ± 19.8</td>
<td>4.5 ± 0.1</td>
<td>4.5 ± 0.1</td>
<td>0.35 ± 0.09</td>
<td>1,016.6 ± 32.2</td>
<td>152.1 ± 8.4</td>
</tr>
<tr>
<td>Oil well #4</td>
<td>378.4 ± 10.5</td>
<td>13.6 ± 0.4</td>
<td>19.4 ± 0.2</td>
<td>ND</td>
<td>1,007.8 ± 20.7</td>
<td>144.3 ± 6.1</td>
</tr>
</tbody>
</table>

$^a$Average ± standard deviation.

$^b$ND, not detected.
TSS is attributed to the presence of Ca with a content of above 80% of total weight. The X-ray diffraction (XRD) patterns of the collected TSS samples from the effluent of the WTP and injection well water samples are illustrated in Figure 2, showing that the composition of the TSS in the samples is mainly calcium carbonate (CaCO$_3$) (Cui et al. 2012). While the contribution of Mg to TSS in the samples is much less than that of Ca, increased iron from the drainage outlet of the WTP to the injection well is likely from the pipeline corrosion (Tao et al. 2011). No crystalline substance was detected in the treated effluents, as shown in Figure 2. Hence, we conclude that the major composition of TSS in water samples is dominated by CaCO$_3$ and iron oxide.

The composition of pipe scale samples was analyzed by X-ray fluorescence (XRF), and the corresponding results are given in Figure S2 (available with the online version of this paper). The results show that the composition of pipe scale consisted of iron oxide, CaCO$_3$, organic matter, NaCl, SiO$_2$ and some other minor metal oxides. The content of CaCO$_3$ is 10.87%, which explains the decline of Ca with the increase in transportation distance. Meanwhile, we found a large amount (49.07%) of iron oxide in the pipe scale, suggesting that the pipe scale in the distribution system is dominated by the corrosion products of the cast iron pipeline. This is in line with Niu et al. (Niu et al. 2006) and Sarin et al. (Sarin et al. 2001). In addition, the content of organic matter is 20.12% in the pipe scale, which is probably due to the presence of microorganisms and the attached oil residue on the wall of the pipeline. The above results indicate that the composition of the pipe scale is comparable with that of TSS, suggesting that the increased content of TSS in the water distribution system is likely from pipe scale and corrosion products, subsequently leading to the deterioration of water quality in the pipeline of the distribution system.

**Effects of microorganisms on the injection water deterioration**

In order to investigate the influence of microorganisms on the deterioration of reinjection water, SRB, FB and TGB in the water samples were analyzed accordingly. The results are shown in Table 3. SRB have been considered to be associated with the promotion of pipeline corrosion (Lytle et al. 2005; Yang et al. 2014). Sun et al. (2017) reported that the growth of SRB can result in a gradually heavy metal release from corrosion scales. Our data show that SRB were not found in the TS and the reinjection well, indicating that SRB barely contributes to the pipeline corrosion. The contents of SRB and FB were found to be lower than that suggested by the national standard SY/T 5329-2012, while...
TGB increased greatly along the pipe from transfer stations to water reinjection wells. The deterioration of water quality probably leads to the regrowth of TGB (Lu et al. 2014). It suggests that the metabolites of TGB can not only cause the increase of TSS, but can also lead to the formation of biofilm on the pipeline (Liu et al. 2014). Moreover, this can cause significant growth of SRB on the pipeline. Hereby, our results suggest that the high concentrations of TGB in water samples are likely due to the increased population of microorganisms in the pipe scale.

**In-situ scale formation and pipe corrosion**

In-situ coupon testing is useful to reveal the influence of water quality change on pipeline corrosion and scale formation. The images of the coupons for the corrosion and scale formation tests are shown in Figure S3 (available with the online version of this paper), and the calculated results of corrosion and scale formation rates are illustrated in Figure 3. It can be seen from Figure S3(a) where there are a lot of hollows on the surface of the coupon, and the corrosion rate of the pipeline increases from 0.36 to 1.45 mm/a with increasing delivery distance from the effluent of the WTP to the rejection well, which is significantly higher than that reported in the literature (Wang et al. 2016). The above results are sufficient to illustrate the increased corrosion of the pipeline during the transport of the treated reinjection water. On the other hand, a thick layer of scale on the surface of the coupon was observed from the scale formation tests (Figure S3(b)). The scaling rate increases from 0.04 to 1.65 mm 1/a along the pipeline with the transport of reinjection water. This is in line with the finding of the corrosion rate (Figure 3). The results herein further confirm that the deterioration of water quality in the distribution system leads to the increased rates of pipeline corrosion and scale formation. In turn, the severity of pipeline corrosion and scale formation will bring about further deterioration of water quality. Hence, there will form a vicious circle in the water distribution system.

**Engineering implications**

Reinjection water quality is one of the important factors affecting the process and effect of water injection and oil production (Ma et al. 2009; Sah et al. 2012). The average permeability of water in subsurface matrices decreases when injecting with deteriorated water, and the permeability is an important factor affecting the recovery of oil. The increase of TSS content in water will seriously block the micro injection holes, directly affecting the injection pressure. Therefore, TSS content is often used as a key factor determining the deterioration of the water quality of reinjection water (Tao et al. 2011). On the basis of our findings, we reveal that in the contents of TSS, certain ions such as Fe$^{2+}$, Fe$^{3+}$, S$^{2-}$, Ca$^{2+}$ and Mg$^{2+}$ are important to the water quality analysis. The increase of TSS content during the delivery process can lead to the occurrence of water quality deterioration, which is in line with our turbidity data. Pipeline corrosion can be explained by the change in water quality.
of iron concentration, which is highly related with the increase of TSS in the reinjection water samples. The change of Ca and Mg concentrations can be used to analyze scale formation. By monitoring the changes of these parameters, the tendency for pipeline corrosion and scale formation can be determined. Unfortunately, these water parameters are barely considered in the present water standard of oil reinjection water treatment.

CONCLUSIONS

The deterioration of oilfield reinjection water is attributed to the increase of TSS, which is closely related to the change of Ca$^{2+}$ concentration along the pipeline and pipeline corrosion. With the increase in water transport distance, the increase of iron ions indicates the occurrence of pipeline corrosion. TSS in reinjection water along the pipeline are dominated by CaCO₃ and iron oxides. The composition of pipe scale and TSS are similar to each other, it is suggested that TSS may be partly derived from pipe scale. The results of the coupon test show that water quality deteriorated with the increase in transport distance, and pipeline corrosion and scale formation became more and more serious in this process. The findings of this study provide the theoretical basis and technical support for the improvement of the oilfield reinjection water treatment process.

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