Advances in corrosion protection and integrity of Produced water reinjection wells tubing in oil and gas field

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Abstract: The objective is to identify and address the corrosion and perforation of reinjection wells, which frequently necessitate maintenance shutdowns and can even result in pollution of the surrounding environment. To deal with the common challenge in various oilfields, it is essential to understand the corrosive influence of each component of the injected water on the reinjection wells tubing. The three versions of the "Water Quality Indicators for Water Injection in Clastic Reservoirs and Methods of Analysis" had been comparatively analyzed, and targeted anticorrosive methods and strategies for tubing in reinjection wells had been put forward. The objective is to establish a theoretical foundation for ensuring the integrity of reinjection wellbores, prolonging the lifespan of reinjection wells, and reducing the impact on the surrounding environment. The results indicate that the acidic composition of injection water, dissolved oxygen, ions, and bacteria such as the sulfate reducting bacteria exert varying degrees of influence on the corrosion of reinjection well tubing and also result in damage to the integrity of reinjection wells. Additionally, a significant number of scholars have investigated a multitude of programs and measures to enhance the corrosion resistance of reinjection well tubing and address the issue of wellbore integrity.

1. Introduction

The advancement of contemporary industry and the global economy has resulted in a corresponding increase in human demand for crude oil. The enhanced oil recovery has consistently represented a significant challenge in the context of global oil extraction. Among the various approaches to this challenge, the reinjection of produced water after treatment is a particularly noteworthy strategy [1-4]. The quality of produced water is complex, containing a variety of components that can have different degrees of corrosive effects on the injection wellbore, injection pipelines, and other parts of the injection well. The integrity of the injection wells is also a concern, as it can lead to challenges such as water leakage from the injection wells and other problems [5, 6]. Approximately 10,000 water injection wells in China are experiencing a range of corrosion-related issues. The average corrosion rate of the production system in the Zhongyuan Oilfield is 1.5-3.0 mm/a, with a pitting rate of 5-15 mm/a. This has resulted in the inability of many tubing reinjection wells to function as intended. With approximately 41.3% of Daqing oil field rejection wells are affected by corrosion, and the corrosion rate of ordinary carbon steel tubing reaching 4.06 mm/a. This has led to a significant impairment of the tubing and casing's integrity, increasing the risk of leakage and soil and water contamination [7]. In light of the aforementioned issue, the turnover of the water quality indexes of reinjection water in the three versions of "Water Quality Indexes and Analysis Methods for Water Injection in Clastic Reservoirs." were compared, and the corrosive effects of each component of the injected water on the tubing of reinjection wells were analyzed. Finally, a series of targeted anti-corrosion methods and strategies for tubing of reinjection wells

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were presented, which provide a theoretical basis to ensure the integrity of reinjection wellbores, extend the life of reinjection wells, and reduce the impact on the surrounding environment.

2. Evolution and Analysis of Specific Parameters in "Water Quality Specifica - tions and Analysis Methods for Water Injection into Clastic Reservoirs"

Table 1 shows the earliest prototype from 1979, followed by the successive revisions and comparisons of the four industry standards SY/T 5329—88, 94, 2012, and 2022 for "Water Quality Specifications and Analysis Methods for Water Injection into Clastic Reservoirs" issued by the National Energy Administration[8,9].With the gradual deepening of oilfield water injection development theory and decades of practical experience, water injection quality indicators have become increasingly scientific and refined. Originally comprising three parameters—mechanical impurities, iron content, and oil content—they expanded to over ten indicators by 1988. Subsequently, the number began to decrease in 1994, reaching just four indicators by 2022. These metrics have grown progressively more targeted and scientifically grounded. Among them, suspended solids (primarily comprising clay minerals, microorganisms, corrosion and scaling products, and organic matter) have gained increasing attention. These particles can cause localized deposition leading to under-scale corrosion while also clogging formations.

Their permissible concentration has progressively increased across successive standards for reservoirs with identical air permeability, rising from a maximum of 10.0 mg/L in the 1994 edition to 35.0 mg/L in the 2022 edition. Similarly, the median particle size of suspended solids has risen, peaking at 5.5 μm in the 2022 edition compared to 3.0 μm in the 1994 edition. This indicates that the broad requirements for suspended solids necessitate enhanced protection against under-scale corrosion. For the SRB in the 2012 edition, the control limit is ≤25 cells/mL when reservoir air permeability exceeds 0.05 μm². which would cause severe pitting corrosion under the 1994 standard. Oil content standards have been relaxed for higher air permeability in several editions. Except for versions prior to 1985, the average corrosion rate was 0.07–0.125 mm/a. while all subsequent versions set the average corrosion rate control limit at ≤0.076 mm/a under any conditions. However, the pitting corrosion criteria were removed from the 2012 and 2022 editions due to the current challenges in quantitatively measuring pitting corrosion and the lack of unified standards. This does not imply pitting corrosion is unimportant; further research on pitting corrosion remains necessary in subsequent studies. Comparing dissolved oxygen (DO), H_2S, and corrosive carbon dioxide content standards between the 1994 and 2012 editions reveals that despite nearly two decades of development, only the DO standard for wastewater or produced water has shifted from "concentration preferably less than 0.05 mg/L, not exceeding 0.10 mg/L" to "less than 0.10 mg/L," indicating the significant impact of these three factors on wells. The standard was only slightly relaxed. In the 2022 edition, this standard was removed, but a method for evaluating injection water sources was added (see Appendix A of SY/T 5329—2022 "Water Quality Indicators and Analysis Methods for Injection into Clastic Reservoirs" for details). This content highlights that ions can significantly impact water injection through water compatibility, necessitating attention to ions in injection water—particularly those prone to scaling.In summary, targeted corrosion prevention measures should be selected by studying the effects of sulfate-reducing bacteria (SRB),DO, acidic components (H_2S, corrosive carbon dioxide), and ions on the corrosion of reinjection well tubing and well integrity.

3. Influence of injection water quality components on pipe corrosion

Since injection well tubing is mostly made of metal [10]. It is therefore necessary to conduct a detailed study of the corrosion of metal materials in relation to the quality of the injection water. The classification mechanism diagram of metal corrosion is presented in Fig. 1.

Tab. 1 Evolution and Comparison Table of Water Quality Indicators for Oilfield Water Injection

Standard Project	1979	1983	1985	Recommended Standards for Water Quality and Analytical Methods for Water Injection into Clastic Reservoirs																					
				1988			1994									2012					2022				
							k_{ai}(μm²)																		
							≤0.1			0.1~0.6			>0.6												
				≤0.1	0.1~0.6	>0.6	A1	A2	A3	B1	B2	B3	C1	C2	C3	<0.01	[0.01, 0.05)	[0.05, 0.5)	[0.5, 1.5)	>1.5	<0.01	[0.01, 0.05)	[0.05, 0.5)	[0.5, 2.0)	>2.0
Particle diameterP[1]≥0.8(μm)	/	/	/	≤2.0	≤3.0	≤5.0	/									/					/				
Mechanical impurities (mg/L)	<2	/	/	/			/									/					/				
SS(mg/L)	/	<5	2~5	≤1.0	≤3.0	≤5.0	<1.0	<2.0	<3.0	<3.0	<4.0	<5.0	<5.0	<7.0	<10.0	≤1.0	≤2.0	≤5.0	≤10.0	≤30.0	≤8.0	≤15.0	≤20.0	≤25.0	≤35.0
D_{50}(μm)	/	/	/	/	/	/	<1.0	<1.5	<2.0	<2.0	<2.5	<3.0	<3.0	<3.5	<4.0	≤1.0	≤1.5	≤3.0	≤4.0	≤5.0	≤3.0	≤5.0	≤5.0	≤5.0	≤5.5
Oil(mg/L)	<30	<30	<30	≤5.0	≤10.0	≤16.0	<5.0	<6.0	<8.0	<8.0	<10.0	<15.0	<15.0	<20.0	<30.0	≤5.0	≤6.0	≤15.0	≤30.0	≤50.0	≤5.0	≤10.0	≤15.0	≤30.0	≤100
r_{corr}(mm/a)	/	0.07~0.125	0.07~0.125	≤0.076																					
Pitting	/	/	/	/			A1 , B1 , C1 : no pitting A2 , B2 , C2: slight corrosion A3 , B3 , C3 : obvious pitting.									/					/				
SR(mm/a)	/	<0.5	<0.5	/			/									/					/				
SRB (CFU/mL)	<5		<100	<10^2	<10^2	<10^2	<0	<10	<25	<0	<10	<25	<0	<10	<25	≤10	≤10	≤25	≤25	≤25	/				
IB(CFU/mL)	<100							n×10^2			n×10^3			n×10^4		n×10^2	n×10^2	n×10^3	n×10^4	n×10^4	/				
TGB(CFU/mL)	<200			<10^2	<10^2	<10^2		n×10^2			n×10^3			n×10^4		n×10^2	n×10^2	n×10^3	n×10^4	n×10^4	/				
TB(CFU/mL)	/	/	10000	/			/									/					/				
MF	/	/	>15	≥20	≥15	≥10	/									/					/				
pH	6.8~8.5	/	/	/			/									/					/				
TI(mg/L)	<2	<0.5	<0.5	≤0.5			/									/					/				
DO (mg/L) Mineralization ≤5000	<0.5	/	/	≤0.5			≤0.50(Clear water) ≤0.10(Wastewater or produced water from oil layers)									≤0.50(Clear water) ≤0.10(Preferably 0.05, wastewater or produced water from oil layers)					/				
DO (mg/L) Mineralization >5000	<1.0	/	/	≤0.05																	/				
ACO_2[2, 3](mg/L)	<5	/	/	≤10			-1.0 ≤ρ≤ 1.0														/				
H_2S(mg/L)[2,4]	0.1~0.2	/	/	≤10			≤0(Clear water) ≤2.0(Wastewater or produced water from oil layers)									≤0(Clear water) ≤2.0(Wastewater or produced water from oil layers)					/				
Sulfide(mg/L)	/	/	<10	/			/									/					/				

Note：1-The percentage of the volume of suspended particles smaller than or equal to a certain size among the total volume of suspended particles in water.;

2-All are auxiliary indicators. The main control indicators of water quality have met the requirements for water injection, and the auxiliary indicators need not be considered. If the requirements are not met, further detection of auxiliary testing items and indicators can be carried out to identify the cause.Auxiliary testing items for water quality in water injection include：DO, H_2S, ACO_2, Fe, pH.

3-When ACO_2=0, this water is stable; When ACO_2>0, this water can dissolve calcium carbonate and has a corrosive effect on water injection facilities; When ACO_2<0, carbonate precipitation occurs.

4-When iron bacteria act on water containing ferrous iron, the divalent iron can be converted into trivalent iron, thereby forming iron hydroxide precipitate.When sulfur compounds (S) are present in the water, FeS precipitation can occur, resulting in an increase in suspended solids in the water.

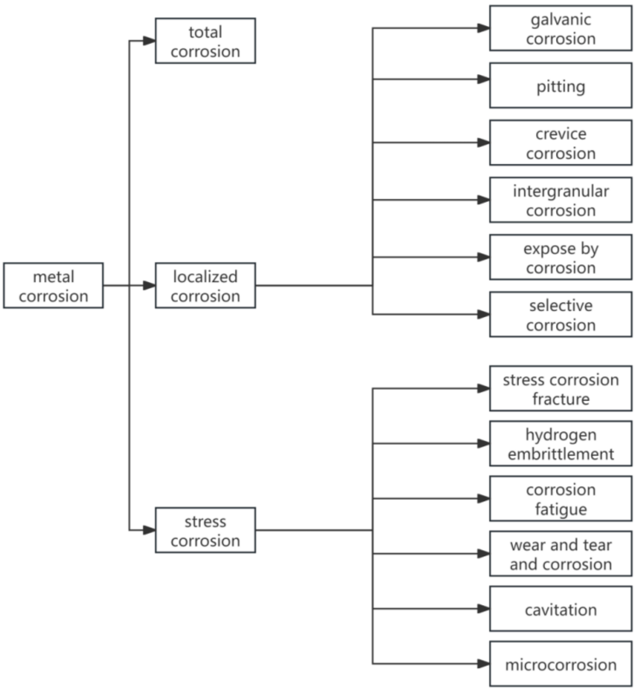

Fig. 1 Classification mechanism diagram of metal corrosion [11]

3.1 Corrosion mechanism of pipes by acidic components in injected water

Although the injection water is treated before the reinjection, it still contains a large amount of acidic components, the main components being CO_2 (sweet corrosion) and H_2S (acid corrosion) [10, 12].

3.1.1 Corrosion mechanism of CO_2 in injected water on pipes

The corrosion of CO_2 on carbon and low-alloy steels is largely dependent on the formation of a surface film during the corrosion process. The corrosion reaction mechanism of CO_2 is as follows:

CO_2 dissolves in water: $CO_2 + H_2O \rightarrow H_2CO_3$

Carbonic acid ionization: $H_2CO_3 \rightarrow H^+ + HCO_3^-$ $\quad HCO_3^- \rightarrow H^+ + CO_3^{2-}$

Anode: $Fe \rightarrow Fe^{2+} + 2e^-$

Cathode: $2H^+ + 2e^- \rightarrow 2H$

Corrosion products: $Fe^{2+} + CO_3^{2-} \rightarrow FeCO_3$

This is a more potent corrosive agent than strong acids, as the corrosion process of metals by strong acids results in the formation of protective corrosion products, which mitigate the corrosion rate. The corrosion product film formed by $FeCO_3$ is relatively loose and thus unable to fulfil a protective role in the metal, thereby failing to reduce the corrosion rate. As the concentration of CO_2 increases, so too does the corrosion rate of the steel sheet, resulting in electrochemical corrosion [13, 14].

CO_2 corrosion is primarily manifested in the form of general corrosion and three distinct types of localized corrosion, namely pitting, tablecorrosion and flow-induced localized corrosion, as illustrated in Fig. 2 [15].

(a) Pitting corrosion (b) Land corrosion diagram (c) Flow-induced localized corrosion

Fig. 2 Illustration of three forms of localized corrosion occurrence

The following parameters have been identified as affecting CO_2 corrosion: fluid composition, pH, water wetting, hydrocarbon properties, temperature, and corrosion film morphology. It should be noted that all of these parameters interact with each other, and that the effects of any one parameter can be compounded by the others [16, 17].

3.1.2 Corrosion mechanism of pipes by H2S in injected water

H2S is highly corrosive when dissolved in water, and it is more soluble than both O_2 and CO_2. H2S is not only highly corrosive to steel, but it also functions as a highly effective hydrogen permeation medium. The electrochemical corrosion of steel by a H2S aqueous solution results in the production of hydrogen. The absorption of hydrogen atoms by steel results in the destruction of its basic continuity, which in turn leads to hydrogen damage and stress corrosion cracking, thereby affecting the safety of the corroded material [13, 18]. The corrosion reaction mechanism of H_2S on some pipes is as follows:

$$2H^{+}+2e^{-}\rightarrow H_{2}(or2H)$$

The adsorption of H2S on the surface enables the subsequent adsorption of hydrogen on ferroalloys. The cathodic rate is contingent upon a multitude of variables, including the electrochemical potential (E), temperature, and pH, in addition to the concentration of the weak acid that provides H^+[20]. The anodic reactions considered are those pertaining to the major alloying elements, namely iron, nickel and chromium. The reactions are expressed in terms of the corrosion products that are most commonly observed, namely:

$$Ni+H_{2}S\rightarrow NiS+2H^{+}+2e^{-} \qquad Fe\rightarrow Fe^{2+}+2e^{-} \qquad 2Cr+3H_{2}O\rightarrow Cr_{2}O_{3}+6H^{+}+6e^{-}$$

The corrosive environment of H_2S can result in varying degrees of uniform and localized corrosion of wellbore casing, tubing, production pumps and grounding valves, as well as tubing. Additionally, stress corrosion cracking (SCC) of tubing at elevated temperatures and pressures has been observed. Furthermore, a synergistic effect between the various acids has yet to be investigated. However, it is established that the presence of multiple acids results in a considerable acceleration of the corrosion rate of the wellbore, leading to severe corrosion [19, 21]

3.2 Corrosion mechanism of pipes byDO in injected water

From the "clastic reservoir injection water quality indicators and analytical methods", it can be seen that the presence of DO in the water can exacerbate corrosion, when the corrosion rate does not meet the standard, the first test should be the content of DO, the oil reservoir extraction waterDO concentration is preferably less than 0.05mg/L, can not be more than 0.10mg/L.DO in the water to be less than 0.50mg/L. TheDO in clear water should be less than 0.50mg/L.

This is because O_2 absorption corrosion occurs when wellbores are subjected to injection water containing saturated DO. O_2 is a strong oxidizing agent and reacts rapidly with metals. O_2 dissolved in the water film on the surface of carbon steel electrochemical corrosion [22], and its corrosion rate is two to four times the average rate; at this time, if the concentration of sodium chloride in the water is less than 10%, it will further accelerate the rate of electrochemical corrosion, which will seriously shorten the service life of the injection pipeline. It will also cause fatigue fracture of the well barriers, sealing failures and other problems such as failure of the wellbore's integrity. Some studies have shown that the wellbore corrosion law is different, the production stage is mainly CO_2/H_2S and other media generated corrosion, the water injection stage is mainly DO corrosion, From a general point of view, the water injection well corrosion is mainly O_2 corrosion of the water injection well stage (injection of water injection wells more than half a year, the amount of water injection corrosion amounted to the total corrosion of more than 90%) [6, 22, 23].The reaction mechanism is:

Anode: $Fe \rightarrow Fe^{2+} + 2e^-$

Cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$$

$$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 \downarrow$$

O_2 solubility in water depends on pressure, temperature and chlorides. When Cl^- is present, it accelerates corrosion by destroying the $Fe(OH)_3$ precipitation protective film, while O_2 usually causes localized corrosion to occur [24].

3.3 Corrosion mechanism of pipes by ions in injected water

The injected water contains a substantial number of ions, which have the potential to exert corrosive effects on the wellbore tubing. To illustrate, the ions present in the injected liquid, including Cl^-, Ca^{2+}, Mg^{2+}, Na^+, and K^+, can readily form a proto-cell effect in re-injection wells when anions and cations coexist. This phenomenon can lead to electrochemical corrosion of the wellbore. The wellbore is susceptible to electrochemical corrosion. Additionally, the dissolution of minerals in the water results in a reduction in pH, leading to the extraction of acidic water from the oilfield. This acidic water is prone to chemical corrosion with the wellbore [25-27].

The injection of Cl^- into the water results in a high level of permeability, facilitating the adsorption of Cl^- on the surface of iron. This process leads to the deterioration of the passivation film, which in turn intensifies the local corrosion phenomenon. Specifically, the corrosion caused by Cl^- can be attributed to two main factors. Firstly, it reduces the likelihood of the composition of the surface passivation film or accelerates the damage of the passivation film, which in turn increases the degree of local corrosion. Secondly, it reduces the solubility of CO_2 in the well fluid, thereby weakening the degree of corrosion of carbon steel. In the case of a low Cl^- concentration (5000 mg/L), the steel surface corrosion film is dense and exhibits strong adhesion ability, as well as good resistance to corrosion. Conversely, an increase in Cl^- concentration by a factor of 1 results in a weakened steel surface corrosion film density, which in turn leads to an increased corrosion rate of carbon steel [28-30]. A high chloride content can readily result in electrochemical corrosion of leaching columns and wellhead equipment. However, an increase in chloride concentration to a certain threshold can conversely reduce the solubility of DO, thereby attenuating the cathodic process and consequently lowering the corrosion rate [24].

In addition, Ca^{2+} and Mg^{2+} in the injected water have a strong tendency to scale at higher concentrations, which enhances the corrosion under the scale, and also weakens the overall corrosion rate and strengthens the local corrosion.The corrosion of Ca^{2+} and Mg^{2+} on the tubular columns is on the one hand, and they also make the hardness of the well fluid increase, and the degree of mineralization becomes larger, which makes the Henry's Constant of the CO_2 dissolved in the well fluid become larger. When other maintains constant, Ca^{2+}, Mg^{2+} concentration becomes larger ambassador CO_2 concentration becomes smaller [31].

3.4 Corrosion mechanism of pipes by bacteria in the injected water

The phenomenon of microbial life activity that causes or accelerates the corrosion process of a material is collectively referred to as microbial corrosion.

One such group of bacteria is the SRB, which are collectively defined as bacteria that reduce sulfur-containing oxides to H_2S under anaerobic conditions. Furthermore, SRB in wastewater multiply with organic matter in the water column, and their products can create breeding conditions for aerobe bacteria. It has been demonstrated that SRB can facilitate the corrosion of metals. In the presence of large quantities of SRB in oilfield water, the iron surface is susceptible to the formation of a looser corrosion product scale layer, which then gives rise to the formation of a local battery, thereby accelerating the corrosion process. The corrosion layer of the tubing wall of the reinjection well will manifest as uneven, concave pitting corrosion. The growth and metabolic processes of SRB can result in the production of reactive sulfides, hypophosphites, and other substances, which accelerate the corrosion of the metal [32-33]. Fig. 3 illustrates the microbial corrosion morphology of SRB in field-simulated water samples [34].

Saprophytic bacteria (TGB) is a kind of aerobe bacteria, it produces mucus often attached to pipelines and equipment, dense and difficult to decompose, they adsorb suspended particles in the water, sediment, resulting in clogging of filters and corrosion of equipment in the water injection system, which likewise reduces the amount of water injected and affects the production of crude oil [35].They adsorb suspended particles in water, causing clogging of filters and corrosion of equipment in the water injection system.

The iron bacteria (IB) also create localized anaerobic environments, allowing SRB, which are anaerobic bacteria, to proliferate and accelerate the corrosion of metals. The corrosion mechanism of bacteria is [18, 36, 37] :(1) Cathodic depolarization, which accelerates the cathodic rate-limiting step through microbial action.(2) Formation of closed surface cells where microorganisms form "patchy" surface colonies. Sticky polymers attract and aggregate living and non-living species, creating fissures and condensed cells, which are the basis for accelerated attack.(3) Immobilization of anodic reaction sites, where microbial surface colonies lead to the formation of corrosion pits, is driven by microbial activity and correlates with the location of these colonies.(4) Depositional acid erosion, accelerated by acidic end-products (mainly short-chain fatty acids) of MIC (Microbial Influenced Corrosion) "community metabolism".

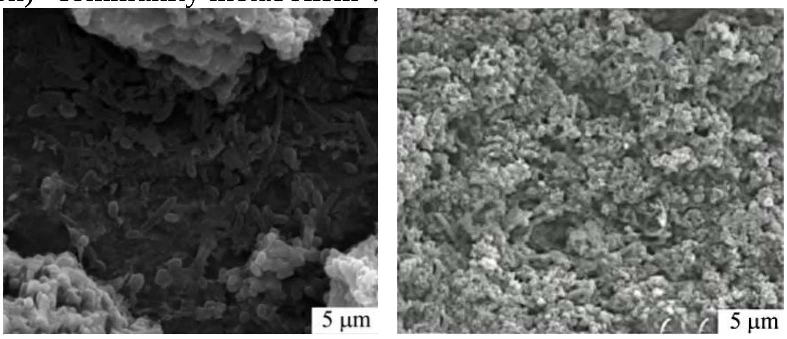

Fig. 3 Microbial corrosion morphology of SRB in simulated water samples from different platforms [34]

4. Pipe Corrosion Protection Measures

4.1 Optimize and improve wellbore materials

In order to resolve the corrosion issues caused by the injection water, it is essential to enhance the corrosion resistance of the wellbore material. In the modern era, alloy oil pipes have become a prevalent material in numerous industrial sectors. In China, alloy tubing is commonly used in oilfield corrosion-prone injection wells, including 3Cr tubing. 3Cr tubing is particularly effective in resisting corrosion from CO_2 and Cl^- and has an extended lifespan of over 30 years. In comparison to other alloy materials, 3Cr tubing is more economical and widely used, which is a significant factor in its use in a greater number of oilfields [38, 39]. In foreign countries, many oilfields utilise corrosion-resistant alloys (CRAs), which are primarily Fe-Cr stainless steel (SS) and Ni-Cr-Mo alloys. These alloys are typically passivated in corrosive environments and effectively protect against hydrogen sulphide corrosion [40].

Tab. 2 Status of use of non-metallic materials

Name	Scope of application	Categorization	Advantage	Disadvantage	Reference
Plastic Polymer Pipe	For wells with high CO_2 content	Polyvinyl chloride (PVC) Polyethylene (PE) Polypropylene (PP) Reinforced thermoplastic (RTP)	Chemically stable Good acid and alkali resistance Good pressure and abrasion resistance Higher stiffness	Toxic and not environmentally friendly	[40, 41]
Fiberglass reinforced plastic pipe	For wells with high CO_2 content and high sulfur content	Fiber-wound fiberglass reinforced plastic Centrifugal cast fiberglass Fixed length fiberglass	Good protection and shielding Good corrosion resistance Low prices	Shorter service life	[40, 41]
Flexible non-metallic pipes	For wells with high alcohol content	Flexible composite high-pressure transportation pipe; Steel skeleton reinforced thermoplastic resin composite continuous pipe	High pressure-bearing; High temperature resistance; Easy construction	Limited range of application and high price	[41]
Nitriding Tubes	Suitable for oilfield water injection wells containing K^+,Ca^{2+},Na^+,Mg^{2+},etc.	Alloy structural steel nitriding tubes; Stainless steel nitrided tubing; Tool steel nitrided tubing; Nitriding pipes for cast iron	Good corrosion resistance; Hardness; Not easy to peel off and easy to transport; Wide range of applications	Not suitablefor wells with high levels of H2S.	[28, 42]

As shown in Tab. 2, it is the current situation in terms of using non-metallic materials. In several oilfields in China, such as the Qinghai oilfield, suitableplastic polymer pipes are selected for water injection pipelines to protect the oilfield water injection system [42].

4.2 Media Controlling Technology

4.2.1 Circumferential space protection fluids

For possible casing corrosion effects:DO corrosion, dissolved salt corrosion and microbial corrosion, the selection of annular air protection fluids as an economical corrosion measure can control all three of these corrosion phenomena [43].

There are various types of annular protection fluid, generally divided into water-based annular protection fluid and oil-based annular protection fluid. Among them, when using water-based annular protection fluid, the corrosion inhibitor annular protection fluid should be filled with the entire oil casing annular space, so that it can form a protective film on the outer wall of the oil pipe and the inner wall of the casing, so as to achieve the purpose of delaying the corrosion of the oil casing [44].

Annulus protection fluids not only inhibit corrosion of the tubing and casing, but also reduce reservoir pressure on the casing head or packer and reduce the pressure difference between the tubing and the annulus. They are selected based on the wettability of the protection location. After the experimental comparison of the performance of many kinds of corrosion inhibitors, HZ series corrosion and scale inhibitors are selected as the annulus protection fluid in most foreign regions [24, 43].

4.2.2 Coating protection

The coating reduces the current required by the cathodic protection system and increases the spacing between anode installations on the pipeline. During its service life, the piping system can be adequately protected when cathodic protection with sacrificial anodes is used [45]. The current status of research on some common coatings for protection is shown in Tab. 3.

Tab. 3 Research status of common coating materials

Name	Scope of Application	Advantage	Disadvantage	Reference
Graphene oxide-based composite coatings	Water injection wells for high sulfur oil wells	Good corrosion resistance and adhesion properties	Currently imperfectly applied	[46]
Fusion Flocculated Epoxy Coating	Deep wells, ultra-deep wells, etc.	Higher mechanical properties	Higher costs	[47]
Titanium nanopaint coating	Suitablefor most wells	Mechanical properties, temperature resistance, corrosion resistance; Good abrasion and impact resistance; Good acid and alkali resistance	Rough surface, needs to solve the problem of protection at the joints of the clamps	[48]

Commonly used anti-corrosion coatings mainly include epoxy powder coating, graphene oxide-based composite coating, fusion-flocculated epoxy coating, and titanium nano-paint coating. Oil companies in South American countries such as Argentina and Brazil provide corrosion and temperature resistance by using and modifying polypropylene related coatings. Liquid coatings of the PC200 series are used in many areas of the United States [49].

4.3 Cathodic protection

The technique of casing cathodic protection was first studied in 1938 in the United States and in localities in the Middle East, and it is currently in use [25]. The technique is subdivided into two categories: applied current cathodic protection and sacrificial anode protection. The technique of sacrificial anode protection is relatively straightforward and can be readily implemented. It does not necessitate the use of an applied power supply, rarely induces corrosion interference, and is a widely employed method for the safeguarding of smaller metal structures (generally with an operating current of less than 1A) or those situated in environments with low soil resistivity (soil resistivity of less than 100 Ω-m). A schematic diagram is provided in Fig. 4 for illustrative purposes. To illustrate, the sacrificial anode protector for the outer wall of the oil pipe of TK422 injection well in Taha Oilfield is depicted in Fig. 5. In order to prevent the corrosion shedding of the sacrificial anode, the protector employs the beam cage type. The protection radius of the outer wall of the tubing in the oil-water medium is approximately 200m [50].

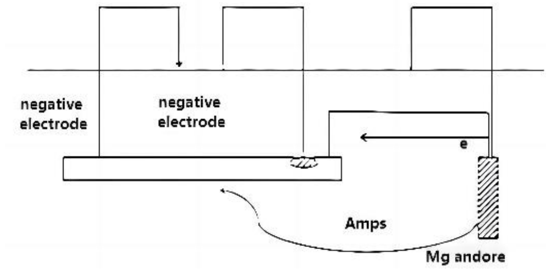

Fig. 4 Schematic diagram of sacrificial anode cathodic protection

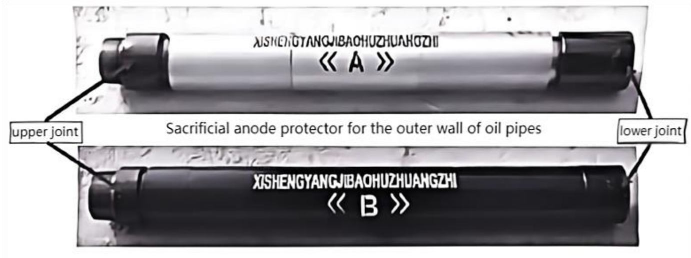

Fig. 5 Sacrificial anode protector for the outer wall of tubing in TK422 injection wells in Taha Oilfield

4.4 Corrosion inhibitors

In China, the prevalent approach involves incorporating a specific quantity of corrosion inhibitor into the sewage. But the corrosion inhibitor is selective, each type of corrosion inhibitor has its own scope of application, so the need for different injection water quality characteristics, pipe materials and the characteristics of the oilfield itself to screen the corrosion inhibitor and through reasonable calculations to derive the rate of corrosion, so as to put the right amount of corrosion inhibitor to play the best inhibition of corrosion effect [50]. The common corrosion inhibitor research status are shown in Tab. 4.

Tab. 4 Research status of some common corrosion inhibitors

form	Example	Application Scope	Reference
High temperature corrosion inhibitor	Mannich base high temperature corrosion inhibitor Quaternary ammonium salt type high temperature corrosion inhibitor Imidazoline-type high-temperature corrosion inhibitors	Good temperature resistance, suitable. for high-temperature deep wells	[51, 52]
Environmentally friendly corrosion inhibitors	Phytate-based corrosion inhibitors Amino acid corrosion inhibitors Natural organic corrosion inhibitors	Less toxic, suitable. for less corrosive wells	[53-55]
CO_2 Corrosion Inhibitors	Imidazoline CO_2 Corrosion Inhibitors Phosphorus-containing compound corrosion inhibitor Alkynol corrosion inhibitors FIQC-APES	For wells with high CO_2 content	[56, 57]
Carbon Point Corrosion Inhibitors	Nitrogen doped carbon point corrosion inhibitors Nitrogen and sulfur co-doped carbon point corrosion inhibitors Metal element doped carbon point corrosion inhibitors	For wells with good H_2S, CO_2, and high salt content	[58-60]

It is important to note that when using corrosion inhibitors, periodic filling of wells without packers with inhibitors through the annulus is necessary. In contrast, for wells with packers, the annulus should be filled with casing annulus protection fluid [19]. Furthermore, in the case of anticorrosion, the same principles apply to anti-waxing. Therefore, the agents used for these processes must be compatible.3.5 Produced water treatment technology [19].

5. Effects of corrosion on wellbore integrity

The occurrence of corrosion not only causes great damage to the wellbore tubing, the well wall including the entire recovery process of the well, but also has a huge impact on the wellbore integrity.

For the impact of corrosive environment on wellbore integrity in reinjection wells. In addition to the anti-corrosion of tubular columns mentioned above, what China's oil and gas industry is currently doing is to promote the quantitative development of wellbore integrity risk assessment methods, and some of the integrity assessment methods are summarized as shown in Tab. 5.

Tab. 5 Wellbore Integrity Test Methods [61-64]

Name	Principle	Advantage	Disadvantage
Standard Annular Space Pressure Test	By applying pressure to a closed annular space (e.g., casing and formation annulus), if there are no leaks, the pressure will remain constant even if the pressure is removed	Results are easy to interpret and inexpensive to implement	Unable to detect bad cementing operations or leaks that bypass the shoe
Radiotracer survey	Adding a radioactive (RA) tracer to the injectant and then using an RA detector to detect the tracer on the downhole line	Ability to detect leaks	Higher costs and difficulties in handling radioactive materials
Temperature recording	Record the temperature gradient of the well to the geothermal gradient as a reference	Ability to detect temperature anomalies or deviations	Difficult to interpret, requires specialized knowledge, can only detect anomalies in temperature gradients
Noise recording	Records sound at different points along the wellbore, where the sound energy travels through the solid, allowing the sensitive microphone to detect turbulence	Little or no off time compared to temperature logging, ability to recognize gas flow and distinguish it from liquid flow	Only turbulent flow can be recognized, closure cannot be proved
Numerical simulation assessment	Is used to model and assess well integrity during fluid injection. This approach considers multiple factors such as mechanical effects, chemical effects and fluid-solid interactions	The results of this method are very precise	The steps are more complex compared to other methods, specifically: model construction, salt rock creep, fluid injection

In recent years, a considerable number of scholars have conducted extensive research on wellbore integrity from a variety of perspectives. The majority of these studies adopt a perspective informed by the disciplines of physics, chemistry and material science. The objective of such studies is to investigate the durability, corrosion characteristics, compressive resistance, fatigue and other factors of wellbore materials. Furthermore, they aim to elucidate the damage patterns of wellbores in long-term mining operations. The resilience of wellbores in the context of natural disasters, such as earthquakes, has also been the subject of investigation. In order to ensure the safety and integrity of wellbores, optimisation measures have been proposed, including seismic reinforcement and seismic isolation separation. However, China has yet to devote sufficient attention to wellbore integrity, and the results achieved have not yet made a significant impact on the international stage. It is therefore imperative to accelerate the research process in wellbore integrity [64].

6. Summary

(1) The injection water of the reinjection wells contains a variety of components, including hydrogen sulphide, CO_2,DO, SRB and other bacteria, ions, and so forth, which exert varying degrees of corrosive effects on the tubing of the reinjection wells. This results in damage to the wells and hinders their normal operations.

(2) Countries are addressing corrosion issues through a multi-faceted approach, encompassing the optimisation and enhancement of wellbore materials and media treatment, the improvement of corrosive environments, the adoption of cathodic protection methodologies, and the examination and conditioning of injection water. This strategy aims to enhance oilfield exploitation efficiency and minimise unwarranted economic and resource losses.

(3) The corrosion problem has had a significant detrimental impact on the integrity of the wellbore, which is highly unfavourable to the normal production of the well. It is therefore imperative that the issue is given due attention and resolved in order to ensure the safety of the wellbore and production.

(4) There is still a lack of awareness among staff of the importance of anti-corrosion measures, particularly in relation to reinjection wells. It is imperative to enhance anti-corrosion awareness and refine anti-corrosion competencies, while intensifying the surveillance of water quality, the examination of reinjection wells, and the regulation of corrosion resistance in wells. It is imperative that the corrosion treatment capacity be enhanced and that an anti-corrosion strategy be optimised in order to guarantee the safety, economy and efficiency of production.

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