A review of prediction methods for oilfield produced water scaling

Yan Yan 1,2, Tao Yu 1,2, Jiayu Song 1, Baichun Wu 1, Chengtun Qu 1,2, *  
1 State Key Laboratory of Petroleum Pollution Control, CNPC Research Institute of Safety and Environmental Technology, Beijing 102206, China  
2 College of Chemistry and Chemical Engineering, Xi’an Shiyou University, Shanxi Oil and Gas Pollution Control and Reservoir Protection Key Laboratory, Xi’an 710065, China  
*Corresponding author e-mail: xianquct@yeah.net

Abstract. In oilfield development, pipeline corrosion and reservoir damage caused by produced water scaling are serious problems. Studying the scaling trend of produced water, and predicting the scaling position, scale amount, and scale type is of great significance to the production and development of oilfields, as well as scale prevention and cleaning. In this paper, the mechanism of scaling in produced water is studied from the perspective of five aspects: fluid incompatibility, thermodynamic condition change, crystal adsorption, kinetic factors and bacterial corrosion; moreover, other factors affecting the scaling are analyzed. Mathematical models of scaling prediction methods, scaling prediction methods, and simulation experiments of scaling prediction methods are introduced, and the characteristics of each scaling prediction method and simulation experiment are compared. Finally, the development of scaling prediction methods is prospected.

1. Introduction  
Most of China's oilfields are currently in the middle and late stages of exploitation, and water injection has been used to maintain formation pressure and increase oil recovery. This leads to new issues arising, such as the ionic reaction that occurs when the water quality is not compatible with the development of the multi-layer system and the scaling issue caused by changes in external conditions (such as temperature and pressure). Scaling leads to pipeline blockage, increased corrosion, and reservoir damage. In severe cases, it can affect the normal production of the oil field and cause significant economic losses. Therefore, it is of great significance for oilfield production and development to study the scaling law of produced water and predict the scaling trend.

2. Oilfield scaling law  
The components of oilfield produced scales are generally insoluble or slightly soluble salts with a fixed lattice and compact texture. The formation of scales in the oilfield water injection system is a complex process and can be divided into the following stages:

(1) In the supersaturated state, insoluble materials precipitate and combine to form salt molecules;
The precipitated insoluble salt molecules are arranged in a regular order to form scale microcrystals;

(3) The scale crystals gradually accumulate and deposit on the tube wall or other parts of the system, forming a visible scale layer [1, 2].

Generally speaking, the scale formation process can be divided into three stages: scale induction period, nucleation stage and crystal growth stage. The formation of scale nuclei and the growth of scale crystals are the most important periods of scale formation [3].

2.1. Scale induction period

The results show that there is a critical state in the supersaturated solution before scaling, and there is no scaling crystal in the solution. Generally, the time between the solution just saturated and the formation of the first scale crystal in the solution is called the scaling induction period [4]. Many factors (such as the roughness of the pipe surface, solution temperature, liquid flow rate, etc.) have great influence on the scale induction period, and directly affect the scale growth. Extending the scale induction period can slow down the scaling rate to a certain extent.

2.2. Formation of scale nuclei

After the completion of the induction period, the supersaturated solution will produce tiny particles in the solution, which is called the crystal nucleus, which is the center of crystal growth. There are two main ways to form scale nucleation: primary nucleation and secondary nucleation. Primary nucleation is the main nucleation mode of slightly soluble salts. There are two forms of primary nucleation, one is spontaneous nucleation, called homogeneous nucleation; the other is heterogeneous nucleation induced by particles. Heterogeneous nucleation is due to the existence of other impurity particles in the solution, which reduces the nucleation potential energy of the crystal, resulting in the rapid formation of scale nuclei [5]. The crude oil and some suspended particles in the produced water of oilfield reduce the potential energy required for scale formation in water. At this time, heterogeneous nucleation and scale nucleation are induced by impurity particles. In the process of sewage transportation, the inner wall of the pipeline is relatively rough, and the scale crystal nucleus is easy to adhere to the inner wall of the pipeline. The increase of the grain concentration in the inner wall of the pipeline increases the heterogeneous nucleation rate of the pipeline surface [6].

2.3. Growth of scale crystals

After a certain scale nucleus is formed in the solution, because the solution is in the supersaturated state, the scale crystal nucleus in the solution further grows into visible scale crystal, and the growth process of the crystal nucleus is called scale crystal growth period [7]. Crystal growth needs to go through the following steps: diffusion, adsorption, reaction and formation of lattice, which can be combined into volume diffusion and ion fusion to produce lattice [8]. Volume diffusion refers to the process of solute diffusion from solution to solid surface. The growth of scale crystal is mainly determined by the concentration difference between solution and solid, so it is mainly controlled by diffusion [9]; the process of forming lattice of fused ions can be regarded as chemical reaction, so it is controlled by reaction [10].

3. The harm of scaling [11, 12]

3.1. The harm of scaling to equipment pipelines

In the process of oilfield water injection development, surface equipment, wellbores, and pipelines are highly susceptible to scaling. This can not only cause the blockage of the equipment and gathering system but also accelerate the propagation speed of SRB and the corrosion rate of the equipment and pipelines. In addition, scaling hinders the corrosion inhibitor from making contact with the metal surface to form a film; thus, the effect of the inhibitor is significantly reduced and can aggravate the corrosion of the equipment and pipelines. Scaling can also reduce the heat transfer rate of the equipment,
shortening its service life and increasing scale cleaning of the equipment and pipelines, and thus increasing the production cost of the oilfield.

3.2. Scaling impact on the reservoir
Most of the oilfields in China are low-permeability reserves. Because low-permeability oilfield pores are very small, when the produced water and reservoir fluid are not compatible, they form small scale crystals attached to the surface of the reservoir core. As water injection develops, these crystals deposit and form a scale layer, which can not only reduce the effective cross-sectional area of the pore channel but also cause the blockage of the pore throat of the reservoir and seriously affect the permeability of the reservoir. In addition, it is difficult to remove the scale, leading to permanent damage to the reservoir.

4. Scaling prediction of oilfield produced water

4.1. Mathematical model [13]
Since the 1930s, the scaling prediction has been widely studied. With the continuous research on scaling prediction methods over the years, more and more reliable prediction methods have been developed. However, all prediction methods have been established based on three basic theories: solubility product rule, ion association theory, and saturation index.

(1) Solubility product rule.
At a certain temperature and pressure, the insoluble electrolyte AmBn(s) has the following chemical equilibrium in solution:

$$A_m B_n(s) \rightleftharpoons mA^{n+}(aq) + nB^{m-}(aq)$$

(1)

$$K_{sp} = [A^{n+}]^m \cdot [B^{m-}]^n$$

(2)

where $K_{sp}$ is the thermodynamic solubility product of the scale-forming substance AmBn(s).

For the insoluble electrolyte solution, the following conditions are used to analyze the scaling trend:

1. When $[A^{n+}]^m \cdot [B^{m-}]^n > K_{sp}$, the solution is supersaturated and has the tendency of scaling;
2. When $[A^{n+}]^m \cdot [B^{m-}]^n < K_{sp}$, the solution is unsaturated and has no scaling tendency;
3. When $[A^{n+}]^m \cdot [B^{m-}]^n = K_{sp}$, the solution is in the equilibrium state of precipitation and dissolution and has no scaling tendency.

The above rules can be used to analyze the occurrence of precipitation and dissolution, which is called the solubility product rule.

(2) Ion association theory
According to the Bjerrum principle, when two ions with different charges are at a certain distance from each other, the Coulomb force between them is greater than the thermal motion force, and a new unit of association can be formed. This new unit has sufficient stability. The common association equilibrium equation is as follows:

$$mM^{n+} + nX^{m-} \rightleftharpoons MX^0$$

(3)

Where $MX^0$ represents the association and is neutral.

(3) Saturation index [14]
The saturation index is an important concept in predicting the oil field water scaling. Based on the basic principles of chemical reaction kinetics, the saturation index can be obtained using the following equation:

$$SI = \log[M_c[A_n]] / K_{sp}(T, P, I)$$

(4)
Where $T, p, I$ (mol/L) are the temperature, pressure, and ionic strength of the scale-forming substance, respectively.

The ionic strength $I$ is given by:

$$I = \frac{1}{2} \sum Z_i C_i^2$$

(5)

where $Z_i$ and $C_i$ (mol/L) represent the valence and concentration of the ions, respectively.

For the insoluble electrolyte solution, the following conditions are used to analyze the scaling trend:

1. when $SI > 0$, the solution is in a supersaturated state and has a tendency to scale;
2. when $SI < 0$, the solution is unsaturated and has no tendency to scale;
3. when $SI = 0$, the solution is in a solid-liquid equilibrium state and has no tendency to scale.

4.2. Evaluation of scaling method prediction method

With years of scientific research, and field application and observation, a mature scaling prediction method has been developed. Single calcium carbonate scaling prediction methods include the Langelier saturation index method [15], Davis stiff saturation index method [16, 17, 18], and Ryznar stability index method [19, 20]. Single sulfate scaling prediction methods include the Skillman thermodynamic solubility method [21]. Mixed scale prediction methods include the Oddo-Tomson saturation index method [22, 23] and OLI ScaleChem scaling prediction software [24].

Langelier saturation index method, which appeared earlier, is simple and widely used, but it is only suitable for predicting single calcium carbonate scale. The pH of water is between 5.5-8.5, and the ambient temperature is 0-100 °C. The formula is an empirical formula, which does not consider the influence of alkalinity and hardness of water, so this method has some limitations.

Davis stiff saturation index method, which combines the ionic strength of water samples to predict the scaling trend of sewage, is also mainly applicable to the prediction of single calcium carbonate scale. Although this method is simple and fast, it only considers the thermodynamic conditions, and does not consider the influence of pressure and fluid flow, so the prediction results have certain errors.

Ryznar stability index method is summarized after a large number of experiments. It not only analyzes the water quality characteristics of oilfield sewage, but also analyzes the influence of factors such as scale formation kinetics and thermodynamics on scale formation. It can not only predict the scale formation of sewage, but also judge whether the water quality is stable. However, this method can only be used to predict single calcium carbonate scale without considering the factors such as mixed crystallization and environmental pressure.

Skillman thermodynamic solubility method can be used to predict the scaling trend of sulfate scale based on solubility. However, this method does not consider the influence of environmental pressure and other factors such as the balance in the sewage on scaling, and there is a large error in practical application, so it can only be used for preliminary judgment.

The Oddo Tomson saturation index method can be used to predict the mixed scale, considering the influence of thermodynamics and other factors on sewage scaling. It is applicable to a wide range of conditions, and can be used under different pressure and temperature conditions. However, the influence of hydrodynamics and crystallization kinetics on fouling is not considered in the prediction method.

In addition, the ScaleChem scaling prediction software developed by the OLI Systems, Inc. (Parsippany, NJ, USA) is widely used in the prediction of mixed scale types. It boasts a powerful database that can simulate the formation conditions according to the water analysis data and predict the possible (or generated) scale type, scaling trend, scale amount, and scaling position [25].

4.3. Experimental research on scale prediction

Compatibility test is an important prediction method to detect the scaling problem of produced water reinjection, which can be divided into static simulation experiment method and dynamic simulation experiment method. The characteristics of the two methods are briefly analyzed, as shown in Table 2.

1. Static simulation experiment method
The static simulation test method, also known as the static bottle test, is performed in the laboratory. First, the ions in the water sample are analyzed to determine the type and salinity of the water sample. Then, the two pre-treated water samples, based on different ratios, are mixed in pairs to simulate the actual temperature of the gathering and transportation system. The mixed samples are stabilized at a constant temperature for a while, and the scale and precipitation are observed and weighed. The static simulation experiment method is a typical method for predicting scaling.

(2) Dynamic simulation experiment method [33, 34]

The dynamic simulation experiment method is also carried out in the laboratory. Based on the static simulation experiment, the actual parameters in the process of gathering and transportation are introduced. The experiment is carried out under constant temperature, and the displacement speed is constant, mainly for alternating the displacement experiment of injected and formation water. The degree of core damage is determined by the decrease of pore permeability. According to the degree of damage to the core by injected water and formation water, the scaling behavior can be assessed. This method uses a scanning electron microscope (SEM) and dynamic scaling experiment instrument.

5. Conclusions

Overcoming scaling in oilfield development is important and the factors affecting the scaling of produced water are complex. It is of great significance to predict the scaling trend, volume, and type of produced water. It is also crucial to strictly control the water quality index of produced water, which is of great significance for timely and fixed-point scaling control and scale removal.

At the same time, each oilfield should combine the scale prediction standard with the actual production and adopt the scaling prediction method accordingly to ensure a sound scientific basis for overcoming scaling efficiently.

In addition, although the prediction methods of oilfield produced water scaling have gradually improved, there are still some limitations. For example, most of the scaling prediction methods are only based on thermodynamic factors and cannot systematically consider crystallization kinetics and fluid dynamic factors.

Therefore, research on prediction methods of oilfield produced water scaling should be combined with the actual production of the oilfield and comprehensively consider various factors. This will develop a wider, more targeted, and more accurate scaling prediction.

Acknowledgements

This paper is supported by State Key Laboratory of Petroleum Pollution Control, CNPC Research Institute of Safety and Environmental Technology, Beijing, China.

References

[1] Tan Z Y. Scaling trend and countermeasures of oilfield water injection system [D]. Huazhong University of science and technology, 2015.
[2] Zhang L, Qu C T, Li Y. Research progress of scaling kinetics[J]. Petrochemical applications, 2015, 34(9): 1-6.
[3] Hu Y, Mackay E J, Ishkov O, et al. Predicted and Observed Evolution of Produced-Brine Compositions and Implications for Scale Management [J]. Spe Production & Operations, 2016, 31(3): 270-279.
[4] Hamid S, De Jesus O, Jacinto C M, et al. A Practical Method of Predicting Calcium Carbonate Scale Formation in Well Completions [J]. Spe Production & Operations, 2016, 31(1): 1-11.
[5] Leng Y X, Tan Q, Huang C X, et al. Determination of metastable zone and induction period of L-tartaric acid aqueous solution [J]. Acta Chem Sinica, 2016, 67(6): 2433-2439.
[6] Wang B. Study on scaling law and prediction method of produced water transmission pipeline in Qiongxi gas field [D]. Southwest Petroleum University, 2017.
[7] Zhang L, Qu C T, Li Y. Research progress of scaling kinetics [J]. Petrochemical applications, 2015, 34 (9): 1-6.
[8] Li S, Li Y, Qu C T. Deposition process of calcium sulfate on Bentonite surface in produced water [J]. Journal of environmental engineering, 2015, 9 (10): 4741-4745.

[9] Yu Tao, Qu C T, Fan D D, et al. Deposition process and influencing factors of scale crystal on clay particle surface [J]. Journal of northwest university (Natural Science Edition), 2017, 47 (5): 699-704.

[10] Al Nasser, Waleed N., Al Salhi, Fahad H. Kinetics determination of calcium carbonate precipitation behavior by inline techniques [J]. Powder Technology, 2015, 270: 548-560.

[11] Wang Y, Qu C T, Hu H J. Research progress on sewage scaling of oilfield [J]. Guangzhou Chemical, 2017, 45(3): 11-13.

[12] Hamid S, De Jesus O, Jacinto C M, et al. A practical method of predicting calcium carbonate scale formation in well completions [J]. Spe Production & Operations, 2016, 31(1): 1-11.

[13] Zhang A M, Liu S Y. Study on scaling properties of produced water from different oil fields [J]. Guangzhou chemical industry, 2015, 43(1): 143–144.

[14] Luo M L. Research and application of formation inorganic scaling prediction technology [J]. Petroleum drilling and production technology, 2001, 23(2): 347–349.

[15] Chen Z X, Xu Y, Shi Z R. Application of scaling trend prediction software in oilfield water injection system [J]. Petroleum engineering technology, 2015 (2): 61–63.

[16] Langelier W F. The analytical control of anti-corrosion water treatment [J]. Journal American Water Works Association, 1936, 28(100): 1500–1521.

[17] Stiff H A, Davis L E. A method of predicting the tendency of oilfield water to deposit calcium carbonate [J]. Journal of Petroleum Technology, 1952, 4(9): 213–216.

[18] Li Z M, Zhang D Y, Qin G S, et al. Studies on the scaling of high pressure and low permeability oil reservoir water injection well [J]. Advances in Petroleum Exploration and Development, 2014, 8(1): 1–8.

[19] Maguire-Boyle S J. Organic compounds in produced waters from shale gas wells [J]. Environmental Science: Processes & Impacts, 2014, 16(10): 2237–2248.

[20] Ryznar J W. A new index for determining amount of calcium scale formed by a water [J]. American Water Works Association, 1944, 36(4): 472–486.

[21] Kamari A, Gharagheizi F, Bahadori A, et al. Determination of the equilibrated calcium carbonate (calcite) scaling in aqueous phase using a reliable approach [J]. Journal of the Taiwan Institute of Chemical Engineers, 2014, 45(4): 1307–1313.

[22] Skillman H F, McDonald J P Jr, Sift H A Jr. A simple, accurate, fast method for calculating sulfate solubility in oilfield brine [C]. Spring Meeting of the Southwestern District. Lubbock, Texas: API, Lubock, Texas, 1969, (3):12–14.

[23] Bedrikovetsky P G, Lopes R P, Rosario F, et al. Oilfield scaling-part I: Mathematical and laboratory modeling [J]. Society of Petroleum Engineers, SPE 81127-MS, 2003.

[24] Oddo J E, Tomson M B. Why scale forms and how predict it [J]. Society of Petroleum Engineers production & Facilities, 1994, 9(1):47–53.

[25] Gao B, Wang Y, Li B, et al. Prediction of scaling tendency in Tianwaitian gas field [J]. Natural gas exploration and development, 2009, 32(1):71-84.

[26] Ma D, Ke L, et al. Evaluation methods and prospects of compatibility and scaling tendency of produced water [J]. Applied Chemical Industry, 2020, 49(1): 234–239.

[27] Liu S Y, Qu C T, Wang J D, et al. Experimental theoretical study on scaling and compatibility of oilfield produced water [J]. Guangzhou Chemical Engineering, 2014, 42(14): 46–48.