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A Physico-chemical Model of Seepage Flows in Reservoirs during Alkaline Flooding

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Abstract In the present paper, we have established a physico-chemical model to describe seepage flows in reservoirs for enhancement of oil recovery (EOR) during alkaline flooding, focusing on the examination of rock /alkaline interation and scale formation. Numerical simulation shows that a few percent enhancement in oil recovery is possible when the alkaline flood technique is applied. However, the reduction of rock permeability for strong alkaline flood is more serious than that for weak alkaline flood. Therefore, the latter should be recommended as a candidate in alkaline flooding.

Key words: oil recovery, alkali agent, strong base, weak base

INTRODUCTION

Alkaline flooding is a EOR technique in which alkali agents, such as sodium hydroxide (NaOH), sodium orthosilicate (Na_4SiO_4) or sodium carbonate (Na_2CO_3) is added into the injected water [1]. The injected alkaline reagents can react with the acidic species contained in the crude oils, resulting in the formation of surface-active soap species. The adsorption of the in-situ produced surfactant can tremendously lower the interfacial tension (IFT) by several orders of magnitude to ultra-low values [2] and change the wettability of the reservoir [3]. This is the main mechanism that caustic chemical flooding may improve oil recovery. Rock/alkali reaction is another important physiochemical phenomenon during alkaline flooding, involving three different mechanisms: ion-exchange, rock dissolution and precipitation of new minerals. In particular, scales can seriously affect the normal operations of the production wells and thus do harm to the reservoir [4]. Field tests have also shown the existence and severity of alkali scales. However, there are few theoretical researches available on this subject thus far. So it is our main objective to further examine the formation of alkali scales and its impact on recovery in alkaline flooding.

In the current article, we firstly discuss how to describe rock/alkaline reactions in the chemical flooding model. Then, numerical simulation is conducted for analyzing scale formation. Finally, we come to some conclusions by the comparison of different consequences during chemical flooding using strong and weak base alkalines.

THEORY OF ROCK DISSOLUTION AND PRECIPITATION

When water containing alkali is injected into reservoir, physiochemical effects between alkali and stratum rock are unavoidable. Ion exchange is an important aspect among alkali/rock interaction. A large number of calcium ions and magnesium ions are replaced by the injected sodium ions through ion-exchange process. This will be helpful to the formation of alkali scale. Rock dissolution and precipitation of alkali scale constitute one of the most important reactions in alkaline flooding. In this paper we will mainly discuss these reactions.

Quartz is the main constituent in many reservoir rocks and consists mainly of SiO_2. In alkaline flooding, the high pH solutions can make the solid SiO_2 dissolve into solution to form amorphous silica. The dissolution of rock reservoir provides a rich source for the formation of silicate scales. The dissolution of solid SiO_2 is a reversible process. The

rate of silica dissolution is zero order and the deposition is first order. It can be described as [5]

$$r = \frac{\mathrm{d}C}{\mathrm{d}t} = k_1 A - k_2 C A \tag{1}$$

In which r is reaction rate, C is the concentration of amorphous silica, t is time, k_1 is dissolution rate constant, k_2 is condensation rate constant and A is surface area.

The formation of alkali scales is a very important phenomenon in alkaline flooding. It has undesirable impacts on the oil exploitation. Usually there are three types of alkali scales: carbonate scales, hydroxide precipitates and silicate precipitates. The silicate precipitates tend to be complex chemically because of the complexity of rock composition. Kaolinite is found in most sandstone strata. So here we take kaolinite for example. In alkaline flooding the dissolution of kaolinite can lead to the precipitation of new minerals such as albite.

$$\mathrm{Al_2Si_2O_5(OH)_4(kaolinite) + 2Na^+ + 2OH^- + 4H_4SiO_4 = 2NaAlSi_3O_8(albite) + 11H_2O} \tag{2}$$

In this paper, solubility product principle is used to depict the formation of scales. We take calcium hydroxide as an example to illustrate solubility product principle.

$$\mathrm{Ca^{2+} + 2OH^- = Ca\,(OH)_2\,(s)} \tag{3}$$

The equilibrium solubility of calcium hydroxide can be written as

$$J = \left[\mathrm{Ca^{2+}}\right]\left[\mathrm{OH^-}\right]^2 = K_{\mathrm{sp}} \tag{4}$$

Where J is the ion product and the brackets denote solution concentration in molar units. K_{sp} is the solubility product constant and it reflects the solubility of insoluble material. If $J = K_{\mathrm{sp}}$, it means that the solution is saturated solution and reaches dynamic equilibrium state. The dissolution rate of calcium hydroxide equals to the deposition rate. No precipitation exists in the solutions. If $J < K_{\mathrm{sp}}$, the solution is unsaturated. There is no precipitation in the solution. And the solution still has the ability of dissolving the calcium hydroxide. If $J > K_{\mathrm{sp}}$, the solution is supersaturated. Supersaturation refers to a solution that contains more of the dissolved material than could be dissolved by the solvent. So crystallization occurs. When cation concentration is $\leq 10^{-5}$ mol/L, cation has completely precipitated.

RESULTS AND DISCUSSION

Based on numerical simulation, it is obviously seen in Table 1 that permeability reduction is observed when the alkali agents are injected. Whether strong base or weak base is injected, the reduction level of permeability increase with the increase of concentration. Another important conclusion is that the degree of permeability reduction of strong base is far more severe than that of weak base.

Table 1. Permeability reduction level when NaOH and Na_2CO_3 injected

Case	Alkali Type	Concentration (%)	Injected pore volume (PV)	Permeability reduction (%)
1	NaOH	0.15	1.5	7
2	NaOH	0.15	2.5	15
3	NaOH	1.00	1.5	18
4	NaOH	1.00	2.5	33
5	Na_2CO_3	1.00	1.5	0
6	Na_2CO_3	1.00	2.5	1
7	Na_2CO_3	5.00	1.5	0
8	Na_2CO_3	5.00	2.5	2.3

Figure 1 depicts the effect of silicate scales to the porosity of the reservoir. It is shown that the silicate scales have a great impact on the porosity nearby the production well. The reason is that after the dissolution of reservoir rock, the dissolved silica exists in the form of amorphous silica in aqueous phase. In general, the amorphous silica precipitates with most multivalent metal cations. The slowly dissolved amorphous silica migrates with the displacement fluid. Eventually the amorphous silica enrich nearby the production well. With the displacement process, the concentration of amorphous silica nearby the production well becomes higher. When the concentration of amorphous silica reaches a certain degree, silicate scales deposit.

Two kinds of alkali agents were used in Daqing oil field. Weak base Na_2CO_3 was used in ZW pilot and strong base NaOH was used in the other pilots. Here we simulate the effect of different types of alkali on the oil recovery. In Figure 2 it is found that the oil recovery will increase with the increase of alkaline concentration whether strong base or weak base are injected. The reason is that the higher the concentration of alkaline solutions means the higher the concentration of hydroxide ion. More surface-active soap species can be produced through the chemical reactions between hydroxide ion and acidic species in the crude oils. More residual oil which were trapped in the strata after water flooding can be emulsified and exploited. Figure 1 also depicts the compare of oil recoveries when 1.0% NaOH and Na_2CO_3 is injected. The oil recovery with strong base is higher than that with weak base. But the difference value of oil recovery between strong base and weak base is small. It is coincide with the field test results in Daqing Oilfield.

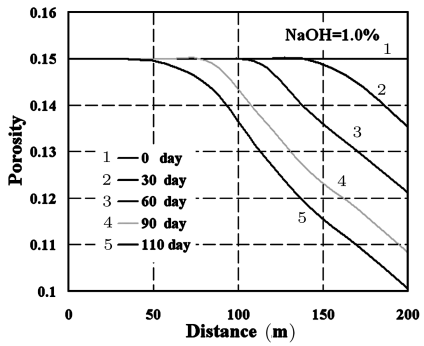

Figure 1: Porosity variation during the displacement process, caused by silicate scales

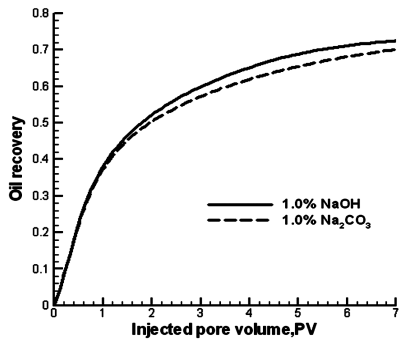

Figure 2: Oil recovery with the same concentration of NaOH and Na_2CO_3 injected

CONCLUSIONS

In this paper, we mainly analyze the effects of alkali scales on reservoir and oil recovery. We find that the silicate scales mainly precipitate near the production wells. The formation of scales can reduce the porosity, pore diameter and permeability. The higher the alkali concentration, the greater the reduction of permeability. The degree of scaling tendency of strong base is far more severe than that of weak base. simulated results show that the difference of oil recovery is little with the same concentration of NaOH and Na_2CO_3 injected. Generally the weak base is strongly recommended.

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