Laboratory study of nitrogen/foam enhanced oil recovery from vuggy-fractured carbonate reservoirs

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Abstract: Aiming at a special vuggy-fractured carbonate, the mechanism of nitrogen flooding, co-injection of water and nitrogen (CWN), water alternating gas injection (WAG) and foam flooding was studied by slate model. Experimental results showed that mechanism of nitrogen flooding was displacing attic oil, which was similar to other vuggy fractured reservoirs. While to CWN, the main mechanism was not relieve of gas channeling. It was found that gas mainly flowed through the upper hole or the upper location of hole and water mainly flowed along the lower hole or the lower location of hole. The main reason why CWN recovery was higher than nitrogen flooding was that during nitrogen flooding, nitrogen would substitute attic oil, so some oil would flow to the water channel and form remaining oil in water channel. During CWN, water flowed mainly along the water channel in previous water flooding, so remaining oil in water channel would not occur during CWN. While to WAG, it had lowest recovery. Among the previous three flooding methods, remaining oil named “sandwich oil” was found between gas and water.

1. Introduction

After water flooding, there are still lots of residual oil in reservoir. Gas flooding is one of efficient substituted EOR methods. Now mechanisms of nitrogen enhanced oil recovery reported in literatures [1-3] are mainly as following. The first one is gravitational differentiation between oil and nitrogen and two elements are included. The first is density difference between oil and gas is larger than oil and water, so gas can sweep “attic oil” at the top and oil will flow to the bottom uniformly. The other element is lower interfacial tension between gas and oil. With lower interfacial tension, gas could overcome capillary force easier and flow into fracture, so gas flooding may have larger sweep efficiency than water flooding. The second mechanism is changing of flow direction. After water flooding, some oil will exist in fracture. When nitrogen flooding replaces water flooding, flow direction of reservoir fluid is changed, so pressure distribution will be changed, which may reduce residual oil saturation. The last mechanism is increase of water flooding sweep efficiency. After nitrogen flooding, connate gas saturation is formed, so both water saturation and relative permeability of water are reduced. From this point, water sweep efficiency could be increased.

However, gas injection has critical problems with poor sweep efficiency, and inefficient displacement of oil in low pressure reservoirs [4]. The process of alternative injection of water and as helps to control of gas mobility [5]. According to the literature [6], the first application of WAG was in North Pembina filed of Alberta in 1957. Another important earlier research is that in 1958, Caudle and Dyes [7] found flowing capacity could be increased by injecting water and gas simultaneously. Besides, in 1962, co-injection of water and gas was applied to field test [8].

Oil recovery by WAG injection has been attributed to contact of unswept zones, especially recovery
of attic or cellar oil by exploiting the segregation of gas to the top or the accumulating of water toward the bottom. WAG injection has the potential for increased microscopic displacement efficiency. M. Sohrabi \[9-10\] used micro-model of high-pressure glass to conduct WAG experiments and all reservoir wettability were considered.

It is similar neither to fractured carbonate in Middle East nor to fractured carbonate in East China. It belongs to vuggy-fractured carbonate. The main reservoir spaces are hole and fracture. At the same time, fracture is the main flow channel of fluid. As to TX oilfield, matrix permeability of all tested cores (without hole or fracture) is lower than 0.0001 mD and porosity is lower than 2%. So, the matrix is of no value in oil reserve or fluid flow. Besides, reservoir temperature is about 130°C and reservoir water salinity is about 220 000 mg/L. Now only a few literatures are found about physical simulation in fracture. However, almost all the experiments didn’t consider the effect of interfacial properties on oil recovery. Because materials used for physical simulation had different properties as carbonate, so the results may not satisfied.

The main purpose of this work is to prepare a carbonate slate model to simulate vuggy fractured reservoir and find out the mechanism of nitrogen flooding, WAG, CWN and foam flooding, which is of significant importance to the TX oilfield development.

2. Experimental section

2.1. Material Used

The mimic brine used in this work was prepared with NaCl, CaCl₂, NaHCO₃ and MgCl₂.6H₂O procured from Sinopharm, and the ion composition of the formation water was shown in Table 1.

| ion content/(mg·L⁻¹) | total salinity (mg·L⁻¹) | pH  | water type |
|----------------------|------------------------|-----|------------|
| Cl⁻ 137529.5         | 223802.8               | 6.8 | CaCl₂      |
| HCO₃⁻ 183.6          |                        |     |            |
| CO₃²⁻ 0              |                        |     |            |
| Ca²⁺ 11272.5         |                        |     |            |
| Mg²⁺ 1518.8          |                        |     |            |
| SO₄²⁻ 0              | 73298.4                |     |            |
| Na⁺⁺+K⁺ 0            |                        |     |            |

2.2. Apparatus and Methodology.

2.2.1. Evaluation of foaming agent

Because the aiming reservoir was high temperature (130°C) and high salinity (about 220 000 mg/L), so lots of surfactants were evaluated and a betaine, named KZF was screened as foaming agent. Foam volume and drainage half-life of various concentration betaine was studied by Warning Blender method. After the foaming solution was treated at 130°C for 15days, foaming ability was studied. Besides, resistance factor of KZF in sandpack was measured.

2.2.2. Preparation of carbonate slate model

15*10*2 cm carbonate slate was prepared by natural carbonate from aiming reservoir. Fracture and hole structure was designed according to TX oilfield. Fracture was about 10 to 100 μm and hole was about 5 to 50 mm. According to cored data, vertical fracture distributed extensively and few horizontal fracture existed. Fracture and hole was carved by laser engraving machine at the two slates. Considering the field conditions, depth and width of fracture was about 1 mm and 0.5 mm respectively. As to hole, depth varied from 5 mm to 10 mm and width was about 0.5 mm. Then the fracture was filled with carbonate particles and cemented by phenolic resin. Then the two slates were cemented by self-made glue. The glue could resist high temperature.
2.2.3. Flooding tests in carbonate slate model
With the natural carbonate slate model, enhanced oil recovery by nitrogen flooding/foam flooding was conducted. In the experiment, mimic water was saturated first, then crude oil was saturated. After aged 48h, flooding test was conducted. Reservoir temperature (130°C) was set as experimental temperature and the back pressure was 2MPa.

3. Results and discussion

3.1. Evaluation of foaming agent
Then sandpack with permeability of 4500md was prepared by the carbonate particle. Resistance factor of KZF foam with different gas liquid ratios at 130°C and 2MPa was measured in the sandpack. The results were shown in Table 2.

| Injected fluid | Gas liquid ratio | Equilibrium pressure/MPa | Resistance factor |
|---------------|----------------|--------------------------|-----------------|
| nitrogen and water | 1:2 | 0.009 | - |
| nitrogen and water | 1:1 | 0.011 | - |
| nitrogen and water | 2:1 | 0.012 | - |
| nitrogen and 0.2%KZF solution | 1:2 | 0.59 | 65.56 |
| nitrogen and 0.2%KZF solution | 1:1 | 0.79 | 71.82 |
| nitrogen and 0.2%KZF solution | 2:1 | 1.18 | 98.33 |

It could be found that all the resistance factors were larger than 60. It meant that KZF foam had good plugging effect and with the increase of gas liquid ratio, resistance factor increased.

3.2. Flooding test in carbonate slate model

3.2.1. Nitrogen flooding after water flooding
First, water flooding was conducted until water cut reached to 98%, then nitrogen was injected. Recovery increment during gas flooding was 18.7%. The results were shown in Figure 2.
3.2.2. Co-injection of water and nitrogen after water flooding
First water flooding was conducted until water cut reached to 98%, then nitrogen and water was co-injected. Recovery increment during co-injection of water and nitrogen was 22.8%. The results were shown in Figure 3.

3.2.3. Alternating injection of nitrogen and water after water flooding
First water flooding was conducted until water cut reached to 98%, then nitrogen and water was injected alternatively. The slug of water and nitrogen was 0.3PV. 6 cycles nitrogen and water was injected totally. Recovery increment during alternating injection of nitrogen and water was 14.3%. The results were shown in Figure 4.
injected alternatively. The slug of water and nitrogen was 0.5PV. 4cycles nitrogen and water was injected totally. Recovery increment during alternating injection of nitrogen and water was 17.5%. The results were shown in Figure 5.

![Figure 5. Production curve of WAG (0.5PV) after water flooding](image)

3.2.4. **Foam flooding after water flooding**
First water flooding was conducted until water cut reached to 98%, then foam with gas liquid ratio 1:1 was injected. Recovery increment during foam flooding was 29.4%. The results were shown in Figure 6.

![Figure 6. Production curve of foam flooding after water flooding](image)

3.2.5. **Comparison**
First, results of nitrogen flooding, CWN and foam flooding were compared and graph was plotted with injected pore volume (IPV) as abscissa and ratio of recovery increment after water flooding to IPV(dimensionless oil recovery) as ordinate. Dimensionless oil recovery may have the similar meaning as production rate. The results were shown in Figure 7. Some regulation could be concluded as following.

(1) Among nitrogen flooding, CWN and foam flooding, from the point of ultimate oil recovery, foam flooding was the best and nitrogen flooding was the worst; from the point of recovery rate, nitrogen flooding was best and foam flooding was worst.

(2) After water flooding, both to nitrogen flooding and co-injection of water and nitrogen, production stage could be divided into 3 stages, namely, water production, oil production and water production. To nitrogen flooding, the first water production stage continued about 0.3PV, while to co-injection of water and nitrogen, the stage was about 0.6PV. Because recovery of water flooding was about 60% (less than 0.6PV), so it meant that some of injected water had been
produced. Gas would mainly existed in the top area of the hole, while water would flow along with the water channel, so it was easier to breakthrough. To both of nitrogen flooding and co-injection of nitrogen and water, oil production stage was not long, but oil production was intensive, so oil recovery could be increased a lot.

(3) To foam flooding after water flooding, production stage could also be divided into three stages. The first water production stage was about 0.4PV, which was longer than nitrogen injection. The reason was that, in nitrogen flooding, nitrogen was easier to breakthrough, while in foam flooding, nitrogen was formed foam with foaming solution and it had lower mobility, so the first water production stage was longer. As to oil production stage, this stage could continue about 1.5PV. Because foam could sweep most of holes or fractures gradually, so oil production stage was much longer.

4. Conclusion
Mechanism of nitrogen flooding, co-injection of water and nitrogen and foam flooding for vuggy fractured reservoir was studied. The main mechanism of nitrogen flooding was displacing attic oil; as to co-injection of water and gas, water could not relieve gas channeling and an important mechanism was preventing remaining oil from gas flooding. In both floodings, “sandwich oil” was formed between water and gas. About foam flooding, foaming solution could restrain gas channeling and foam behaved as a stable phase with various densities, so it had large sweep efficiency in holes and sandwich oil could be displaced.

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