Experimental investigation on the injection profile variation in the weak gel injection process

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Abstract. In this paper, the gel-forming performance and rheological properties of weak gel systems were studied through laboratory gel-forming experiments. The plugging behavior and mechanism of the weak gel system for sand-packed tubes with different permeability were evaluated. The results showed that intramolecular cross-linking was dominated when the polymer concentration was low and the viscosity increased litter after gelation. Intermolecular cross-linking plays a major role when the polymer concentration is high. The injection speed has a great influence on the resistant factor (RF in short) of the weak gel. During low-speed injection, the weak gel has a large amount of retention on the surface of the rock particles, resulting the high viscosity of the weak gel. The RF during low-speed injection is much higher than that in high-speed injection and it keeps increasing as the injection volume increase. The impact of the injection rate on RF of hydrolyzed polyacrylamide (HPAM) is significantly lower than weak gels, because the retention of HPAM in the sand-packed tube reaches a stable level, the RF remains basically unchanged.

1. Introduction

As most of the oilfields in China have entered the high water cut stage, due to the unfavorable oil-water mobility ratio and reservoir heterogeneity, the problem of channeling and bypassing flow would occur, leading to the majority of injected water being absorbed by the high permeability layer and micro-pore in the layer, resulting in low water sweep and oil displacement efficiency [1]. In order to improve the sweep and displacement efficiency of injected water and solve the problems of channeling and bypassing flow, in-depth oil displacement profile control must be carried out [2,3]. The results of laboratory experiments and field pilot tests show that weak gel in-depth oil displacement profile control is an important method to improve the sweep efficiency of injected water and increase the ultimate recovery of water flooding reservoirs [4-6]. This paper conducts experimental research on the weak gel used in polymer flooding wells in LD10-1 oilfield in Bohai Bay. Although the field test of weak gel flooding in the LD10-1 oil field has been successful, some problems of special concern have emerged, such as weak gel blocking the wellbore and formation, weak gel channeling and subsequent water flooding liquid absorption profile problems. These questions have been studied in this paper. This weak gel profile control agent is a three-dimensional

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reticular structure cross-linking system composed of low-concentration polymer and appropriate cross-linker, which is dominated by intermolecular cross-linking and supplemented by intramolecular cross-linking.

Weak gel is a deep profile control agent developed on the basis of conventional strong gel profile control and polymer flooding [7]. Compared with the strong gel, the most notable feature is that it has a certain mobility and can migrate to the in-depth reservoir to block the channeling channel [8]. This technology uses polymer with concentration close to the concentration of polymer flooding, adding a small amount of retarding crosslinking agent to slowly form weak gels in the formation [9]. On the one hand, the weak gel has a certain strength, which can block the high-permeability channels to a certain extent, so that the subsequent injected water can be transferred to the low and medium permeability layers to play a role of profile control. On the other hand, due to the low crosslinking strength, the weak gel can slowly move from the high permeability channel to the deep part of the reservoir under the promotion of the subsequent injection of water, producing the same oil displacement effect as polymer flooding [10].

Profile control is the use of chemical agents with automatic direction selection function to inject chemical agents into water injection wells to make them preferentially enter and block high-permeability layers to achieve the purpose of adjusting water absorption profile and improving oilfield recovery [11]. This process technology uses the ground pump truck to inject the weak gel polymer profile control agent into the water-absorbing layer without changing the original water injection pipe string. Under the formation conditions, the polymer with the cross linker react chemically to form a spatial reticular structure, which can effectively block the high permeability layer and achieve the purpose of adjusting the water absorption profile of the water injection well [12,13]. The slug coordination between "adjustment" and "displacement" can be realized more reasonably. In the aspect of “adjustment”, the main consideration is to limit the water absorption of the high permeability zone and realize the start of the heterogeneous small-layer in the layer, in the aspect of “displacement”, the emphasis is on the influence of the in-plane heterogeneity to improve the subsequent displacement liquid swept volume is increased while enhance the oil displacement efficiency.

2. Experimental section
Through the weak gel-forming experiment and the rheological property test, the change rule of viscosity and flowline characteristics of the weak gel before and after gelation under different polymer concentrations and different RPC (mass ratio of the polymer to Cr³⁺) were studied.

2.1. Materials
The polymer used in the experiment was partially hydrolyzed polyacrylamide (HPAM) with a relative molecular weight of 2.0×10⁷ and an active ingredient of 90.0%. The cross-linker is organic chromium and the active ingredient is 3.6%. The experimental water is a simulated water sample configured according to the ion concentration data provided by the LD10-1 oil field in Bohai Bay.

2.2. Experiments on weak gel formation and rheological properties
The experimental steps of weak gel formation are as follows: first, prepare a mother liquor with a concentration of 7000 ppm with experimental water and aged at room temperature for 24 hours; then, the mother liquor was diluted with experimental water into target solutions with concentrations of 1200 ppm and 3000 ppm, and the cross-linker was added. The amount of cross-linker added was determined by RPC. In the experiment, 180:1, 120:1, 90:1, 60:1, 45:1, and 30:1 RPC were selected to study the properties of weak gels. The rheology measurement equipment is the HAAKE MARSIII modular high-temperature and high-pressure rheometer (Figure 1). The shear rate used in the viscosity test is 1s⁻¹ and 7.31s⁻¹, and the shear rate of the rheological curve is 0.01s⁻¹-20s⁻¹.
2.3. Experiment on plugging characteristics of weak gel
According to the geological characteristics of LD10-1 oilfield, sand-packed with different permeability were used to carry out seepage characteristics experiments at 65°C. By observing the change of injection pressure, the injection capacity and plugging capacity of weak gel in sand-packed with different permeability were investigated, and the characteristics of the resistance factor in sand-packed with injection volume were studied. The permeability of different sand-packed were 300mD, 500mD, and 1000mD. The polymer concentration used for displacement experiment was 1200ppm and the injection rate was 0.1mL/min, 0.5mL/min, 1.0mL/min.

The microstructure of weak gels with different polymer concentrations and different RPCs was studied by scanning electron microscope (SEM). SEM also observed the retention of weak gels in porous media. The equipment used in this experiment is Quanta 200F SEM (FEI, USA), and all samples are prepared by freeze-etching technique.

2.4. Experiment of profile control characteristics of weak gel
Using parallel visible sand-packed with different permeability levels, as shown in Figure 2, a simulation experiment of weak gel profile control was carried out. The seepage behavior experiments system mainly contains injection system, sand-packed tube hander, back pressure system and pressure-acquisition system. The sand-packed tube hander and weak gel cylinder were placed in a thermotank to obtain the reservoir temperature. All the tests were conducted at 65°C.
First, connect the two sand-packed in parallel and saturate them with brine, measure their permeability accurately until they meet 1000mD and 3000mD. The polymer concentration used in the seepage behavior experiment was 1200 ppm, and the RPC was 180:1. A certain amount of weak gel was injected at high speed (2mL/min) and low speed (0.2mL/min) respectively. The gel was aged at 65℃ for 24 hours, thus the gelatinization was carried out. Then a certain amount of brine was injected into the same injection rate, and the profile control characteristics of weak gel under different injection rate were studied. During this period, the liquid produced was collected and measured, and the pressure was measured by the pressure-acquisition system during the seepage behavior experiments.

3. Experimental results and discussion

3.1. Gelation and rheological characteristics
The experimental results are shown in Table 1 that when the polymer concentration is low (1200ppm), dominated by intermolecular cross-linking, and the viscosity changes litter after gelation. When the polymer concentration is high (3000ppm, 7000ppm), intermolecular cross-linking is more, and the viscosity increases greatly after gelation.

![Figure 3. Rheological curves of Weak Gel and HPAM.](image)

When using different shear rates (1s⁻¹, 7.34s⁻¹), the apparent viscosity of weak gels was significantly affected. At the same time, we also compared the rheological properties of weak gel and HPAM at room temperature. It can be seen from Figure 3 that compared with the same concentration of HPAM, the weak gel system has higher viscosity and better thermal stability.

| Polymer type | Polymer concentration (ppm) | RPC | Gelling state | Viscosity (mPa·s) 1s⁻¹ | Viscosity (mPa·s) 7.34s⁻¹ |
|--------------|------------------------------|-----|--------------|------------------------|-------------------------|
| Weak gel     | 7000                         | 60:1| Before gelling | 1305                   | 329                     |
|              |                               |     | After gelling | 105048                 | 10453                   |
|              | 3000                         | 60:1| Before gelling | 160                    | 62                      |
|              |                               |     | After gelling | 6700                   | 1752                    |
|              | 1200                         | 60:1| Before gelling | 23                     | 12                      |
|              |                               |     | After gelling | 25                     | 14                      |
|              | 7000                         | -   | Before gelling | 521                    | 165                     |
| HPAM         | 3000                         | -   | Before gelling | 70                     | 32                      |
|              | 1200                         | -   | Before gelling | 21                     | 10                      |
Figure 4. Microstructure of the weak gel with different polymer concentrations and different RPCs (magnified 1000 times) (a) $cp = 1200$ppm $RPC = 180:1$, (b) $cp = 3000$ppm $RPC = 180:1$

Figure 4 shows the microstructure of weak gel at polymer concentrations of 1200ppm and 3000ppm by SEM. The microstructure of the weak gel in Figure 4a is lamellar. When the polymer concentration is 3000ppm (Figure 4b), the microstructure changes to reticular, the cross-linking between polymer molecules is enhanced, and the strength of the weak gel is significantly increased. We configured weak gel solutions with different polymer concentrations and different RPC concentrations, as shown in Table 2 and Figure 5, and measured the viscosity at different shear rates. We found that the weak gel viscosity increased greatly with the increase of polymer concentration, and increased with the decrease of the RPC (the greater the cross-linker concentration). Although the polymer concentration is high, the reticular structure is more regular, considering the reservoir conditions of the LD10-1 oilfield, the weak gel performance and the economic benefits of weak gel flooding, the field test used weak gel with 1200 ppm polymer concentration and $RPC = 180:1$. Therefore, this concentration of weak gel was used in the subsequent studies of this article.

Figure 5. Viscosity test results of different RPC weak gel.
Table 2. Viscosity test results of weak gel.

| Polymer concentration (ppm) | RPC | Viscosity (mPa·s) Shear rate=1s⁻¹ | Viscosity (mPa·s) Shear rate=7.34s⁻¹ |
|-----------------------------|-----|----------------------------------|----------------------------------|
| 1200                        | 180:1 | 16                               | 8                                |
|                             | 120:1 | 19                               | 9                                |
|                             | 90:1  | 19                               | 9                                |
|                             | 60:1  | 25                               | 14                               |
|                             | 45:1  | 59                               | 26                               |
|                             | 30:1  | 109                              | 49                               |
|                             | 180:1 | 2241                             | 628                              |
|                             | 120:1 | 4920                             | 1051                             |
| 3000                        | 90:1  | 5800                             | 1391                             |
|                             | 60:1  | 6700                             | 1752                             |
|                             | 45:1  | 8691                             | 2045                             |
|                             | 30:1  | 12391                            | 2619                             |
|                             | 180:1 | 45133                            | 6229                             |
|                             | 120:1 | 62975                            | 7988                             |
|                             | 90:1  | 85451                            | 8716                             |
| 7000                        | 60:1  | 105048                           | 10453                            |
|                             | 45:1  | 114587                           | 12637                            |
|                             | 30:1  | 124373                           | 14599                            |

3.2. Plugging behavior of the weak gel

Figure 6. Change of injection pressure during injection of weak gel (injection rate 1mL/min). Water flooding; Weak gel flooding and gelling for 12 hours after each stage; Subsequent water flooding.
Combined with the geological characteristics of the LD10-1 oilfield, three sand-packed with different permeability were used to conduct seepage behavior experiments to study the plugging characteristics of the weak gel in the formation. All the tests were conducted at 65°C. Perform weak gel flooding was carried out after water flooding 2PV. As shown in Figure 6, there are 5 stages of weak gel flooding. After each gel was injected for 12 hours, weak gel was injected. The liquid injection rate was kept constant at 1mL/min, the weak gel system had an extraordinary plugging effect on low permeability (300mD) sand-packed tube. With the continuous injection of weak gel, the low-permeability sand-packed tube injection pressure continues to rise. However, the weak gel system has no significant plugging effect on the high permeability (1000mD) sand-packed tube. After 10PV was injected, the high permeability sand-packed tube resistance factor was about 12 (The resistance factor is defined as the ratio of the differential pressure during weak gel solution injection to the differential pressure during brine injection for the same porous system).

After the displacement experiment, the filled sand was disassembled, and the internal sand samples were obtained and analyzed. As shown in Figure 7, each column corresponds to the same sand packed. It can be seen that the lower the permeability, the smaller the pore space, the more the retention of the polymer and the cross linker, and the more serious the blockage. The retention at injection end with permeability of 300mD is significantly higher than that of sand-packed tubes with 500mD and 1000mD. In addition, in the process of weak gel injection, the polymer and cross linker remain on the surface of the rock particles and block the pores. The pressure at the injection end is significantly higher than that at the production end, and the weak gel has obvious plugging effect on the sand-packed tube injection end. When the weak gel is actually injected in the oilfield, it mainly has obvious plugging effect on the near-wellbore zone, but the plugging range is limited.

![Figure 7. Photos of sand samples with different permeability after injection of weak gel.](image-url)
Figure 8. The gelation state and SEM (where a and c are produced liquid and its microstructure; b and d are flow-back liquid and its microstructure.

It can be seen in Figure 8 that the gelation state of the produced liquid and the flow-back liquid is different, and the microstructure is analyzed by scanning electron microscopy (SEM). The viscosity of the weak gel after shearing through the sand-packed (1000 mD) is 2–3 mPa·s which cannot form gelling at the reservoir temperature (65°C). The viscosity of the flowback liquid at the injection end of the sand-packed is 116 mPa·s, which is significantly higher than the designed weak gel injection system. The reason for the increase in viscosity is that the polymer adsorption and retention at the injection end and is further cross-linked to form a dense reticular structure (Figure 8d).

The injection speed has a great influence on the RF of the weak gel. During low-speed injection, the weak gel has a large amount of adsorption and retention on the surface of the rock particles, and the accumulated gelling viscosity is large. As shown in Table 3, the sand-packed used in this experiment has a permeability of 1000 mD, the RF during low-speed injection is much larger than that during high-speed injection, and it keeps increasing as the increasing injection volume. The impact of the injection rate on RF of HPAM is significantly lower than that of weak gels. When the retention of HPAM in the sand-packed tube reaches a stable level, the RF remains basically unchanged.

Table 3. Variation of RF with injection volume during weak gel and HPAM injection.

| Type   | Injection rate (mL/min) | 2PV  | 4PV  | 6PV  | 8PV  | 10PV |
|--------|------------------------|------|------|------|------|------|
| Weak Gel | 0.2                    | 14.2 | 20.3 | 25.6 | 36.7 | 45.8 |
|         | 0.5                    | 12.2 | 15.4 | 18.3 | 20.5 | 22.3 |
|         | 1.0                    | 10.5 | 10.7 | 10.9 | 11.2 | 12.1 |
|         | 0.2                    | 11.2 | 11.2 | 11.5 | 11.3 | 11.3 |
| HPAM    | 0.5                    | 12.1 | 12.3 | 12.3 | 12.4 | 12.6 |
|         | 1.0                    | 14.3 | 14.3 | 14.5 | 14.6 | 14.6 |

3.3. Profile control behavior of weak gel
A parallel visual sand-packed with different permeability gradation was used to carry out the simulation experiment of weak gel profile control. The parallel sand-packed were filled with glass
beads, the upper one is 1000mD, the lower one is 3000Md. The injected water was dyed red and the weak gel was colorless (Figure 10).

When the permeability ratio is 1000mD/3000mD and the liquid injection rate kept constant at 2mL/min, as shown in Figure 9a, the weak gel enters the high permeability sand-packed tube first, and when the resistance of the high permeability sand-packed tube increases to a certain extent, the gel begins to enter the low-permeability sand-packed tube. However, in the subsequent water flooding process, the injected water only enters the high permeability sand-packed tube, and the low permeability sand-packed tube does not absorb liquid.

![Diagram](image)

**Figure 9.** Relationship between production rate, injection pressure, and PV. Case 1: (1000mD/3000mD; 2mL/min); case 2: (1000mD/3000mD; 0.2mL/min)

During the low-speed (0.2mL/min) injection process. In the initial stage, the proportion of weak gel entering the high permeability sand-packed tube is large, first gradually decrease, then gradually increase, and finally remain basically stable. In the subsequent water flooding, only the high permeability sand-packed tube absorbs water (Figure 9b).

A conclusion can be drawn from the above discussion: whether it is high-speed injection or low-speed injection, the low permeability sand-packed tube injection profile has only one reversal.
4. Conclusions
The weak gel properties test and seepage behavior experiments in this article clarified the characteristic of injection profile, main control factors and change mechanism of weak gel flooding in LD10-1 thick reservoir, the following conclusions can be made:

1. Intramolecular cross-linking is dominated when the polymer concentration is low (1200ppm) and the viscosity increase litter after gelation. Intermolecular cross-linking plays a major role when the polymer concentration is high (higher than 3000ppm). The viscosity of the gel system increases dramatically and the apparent viscosity is significantly affected by the shear rate. Intermolecular cross-linking is the dominant role in the weak gel system, so its shear stability is better than the same concentration of HPAM solution.

2. The injection speed has a great influence on the RF of the weak gel. During low-speed injection, the weak gel has a large amount of retention on the surface of the rock particles, resulting the high viscosity of the weak gel. The RF during low-speed injection is much higher than that in high-speed injection and it keeps increasing as the injection volume increase. The impact of the injection rate on RF of HPAM is significantly lower than weak gels. When the retention of HPAM in the sand-packed tube reaches a stable level, the RF remains basically unchanged.

3. Liquid can be injected in both sand-packed tubes in the initial stage of weak gel injection but the high permeability sand-packed tube can absorb more liquid. As the injection continues, the liquid absorption ratio of low permeability sand-packed tube reduced gradually. The low permeability sand-packed tube does not absorb liquid any more when the injection mount is more than 2.0PV, the injection profile reversal could not happened during the subsequent water flooding. The injection liquid were all absorbed by the high-permeability sand-packed tube during the subsequent water flooding.

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