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# Plugging Behavior of Polymer Gel in Fractures by Multi-Slug Injection

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## Abstract

In order to understand the plugging mechanism, experiments of multi-slug gel plugging in single fracture and multiple fractures system were simulated by indoor visual fracture models. The experiments showed that there were two stages in the process of multi-slug gel plugging in single fracture: gel filling stage and gel compaction stage. When the total injection of gel is consistent, the brine flooding pressure gradient after multi-slug gel injection increased more than 2 times than the pressure gradient after single slug gel continuous injection. While there were three stages in the process of multi-slug gel plugging in multiple fractures system: Gel selectively entrance stage, gel filling stage and gel compaction stage. However, there would be no gel compaction stage, even no gel filling stage in the process of single cycle gel plugging in multiple fractures system.

**Key words:** Fractured reservoir; Multi-slug; Polymer gel; Plugging process

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## INTRODUCTION

Low permeability fractured reservoir, as a kind of unconventional resource, received more and more attention in recent years[1]. And numerous techniques have been developed and adopted to improve the efficiency of water flooding in low permeability fractured reservoirs[2-3], in which gel in-depth profile control technology is the most popular and efficient one in use[4]. Studies indicated that the success of gel treatments in fractured reservoir depends on the performance of gel propagation through fractures and plugging ability of gel in fractures[5-6]. For the former, scientists conducted research on the flowing performance of gel in fractures or fractured formation. Seright et al., since the early 1990s, carried out a series of experimental studies about Cr(III)-acetate-HPAM gels propagation through fractures with fractured cores. They observed the pressure gradient behavior during injection of gel and its sensitivity to flow rate and matrix permeability, shear-thinning behavior of gel in fracture correlated with gel velocity and fracture width, and gel dehydration[7-8]. Researchers at the University of Kansas had also conducted extensive studies to understand the extrusion of gels through fractures, tubing, and high-permeability sandpack[9-10]. Experimental results had also been reported on particle gels transportation through porous media and open fractures[11]. In addition to the performance of gel propagation through fractures, the plugging ability of gel in fractures was also important to profile control in fractured reservoir[12-13]. In fractured low permeability reservoirs, it had been confirmed that the effect of just injecting gel by single slug was sometime poor, and then the multi-slug gel profile control technology developed in recent years[14]. The multi-slug gel profile control is a kind of method that gel is injected by multi-cycle with small slug, through which channeling-path in different level fractures is plugged correspondingly, the permeability difference between different level fractures is reduced, pressure gradient of formation is increased step by step, and the water flooding sweep efficiency and oil recovery are improved. At present, reports of the technology were mainly the development of profile control agent and some field tests, but no laboratory results had been reported on the mechanism of profile control with multi-slug gel in fractures.

The objective of this study is to visualize multi-slug gel plugging in fractures and analyze the correlative factors. By the visual fracture model, which was composed by two glass plates that were not permeable, the profile control law of multi-slug gel in single fracture and multiple fractures system was studied, and the mechanism of plugging and profile control was discussed.

## 1. EXPERIMENTAL

### 1.1 Materials

To simulate formation brine of a certain low permeability field, the brine used in experiment was prepared with salinity 41,811.5 mg/L, PH6.8, whose ion composition was showed in Table 1.

**Table 1**
**The Ionic Composition of Formation Brine Used for Experiments**

| Ion types | $K^++Na^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Cl^-$ | $SO_4^{2-}$ | $HCO_3^-$ |
|---|---|---|---|---|---|---|
| Ion content, mg/L | 5,970.3 | 9,468.9 | 30.4 | 25,967.1 | 120.1 | 189.2 |

HPAM, with molecular weight 14 million, provided by BAOMO Company in Chinese.

The organo-metallic crosslinker used for the experiments was self-made.

Naphthol green B, NaCl, KCl, $CaCl_2$ and $Na_2SO_4$ were provided by Sinopharm.

The profile-controlling agent used for the experiments was made from HPAM and organo-metallic crosslinker, at 25 ℃ and PH 7, with 3,000 mg/L HPAM and 50 mg/L crosslinker.

### 1.2 Experimental Setup

The experimental setup was composed of fracture simulation model, injection system and test system. The fracture simulation model was made of two single-sided frosted glass plates, with characteristics of visible and controllable width, whose size was 300 mm × 45 mm. The model was packaged by epoxy resin after copper wire with different diameter embedded between glass plates, which was used for controlling the fracture width.

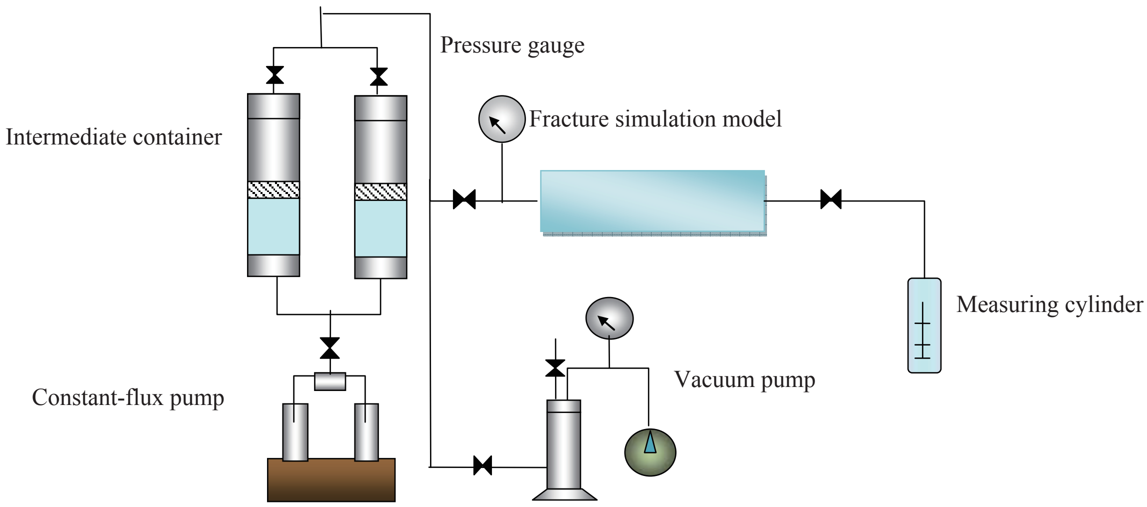


**Figure 1**
**Experimental Flow Chart**

### 1.3 Experimental Procedure

(a) The brine prepared before was injected into the model with a fracture width of 80 μm, and then weak gel was extruded into the fracture model with rate of 0.1 ml/min until the weak gel injection volume reached 2.0 PV. After weak gel was cross linked completely, brine was injected with rate of 1.0ml/min until the pressure was stable. The pressure and the distribution of gel in the fracture were recorded during the whole brine flooding process.

(b) Similar to the first part, the total injection volume of weak gel remained 2.0 PV, but the injection mode of weak gel into fracture was changed, which would be two cycles with two slugs, four cycles with four slugs and eight cycles with eight slugs. Brine was injected with rate of 1.0 ml/min until the pressure was stable after each gel slug.

(c) Three fracture models with different width (80 μm, 150 μm, 330 μm) were connected in parallel to study the profile control mechanism of weak gel in multiple fractures system step by step. The total injection volume of weak gel was 1.0 PV, by eight cycles and eight slugs, with injection rate of 0.1 ml/min, and the injection rate of brine was 1.0 ml/min.

## 2. PROFILE CONTROL RULE OF MULTI-CYCLE GEL INJECTION IN SINGLE FRACTURE

Figure 2 shows the pressure gradient in the fracture during brine flooding after gel injection with different injection modes: One cycle with one slug, two cycles with two slugs, four cycles with four slugs and eight cycles with eight slugs (the total gel injection volume was all 2.0 PV). The last pressure gradient during brine flooding, after gel injection with different modes mentioned above, was respectively 46 kPa/m, 52 kPa/m, 73 kPa/m and 107 kPa/m. Obviously, the brine flooding pressure after multi-cycle with multi-slug gel was higher than that after single slug gel, what's more, with the increasing number of cycles and slugs, the pressure would be higher.

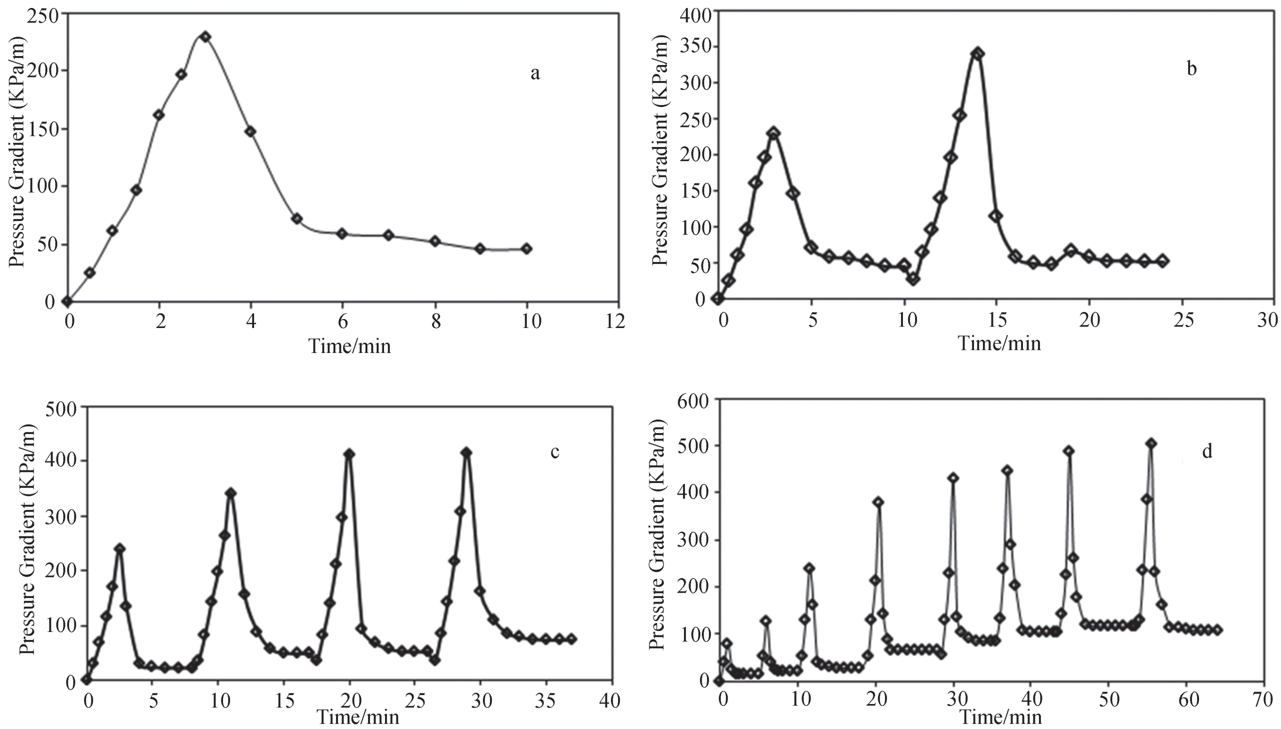


**Figure 2**
**Pressure Behavior During Brine Flooding After Gel Injection With Different Injection Modes, and the Four Condition Can Be Expressed as: (a) One Cycle and One Slug; (b) Two Cycles and Two Slugs; (c) Four Cycles and Four Slugs; (d) Eight Cycles and Eight Slugs**

Take the brine flooding pressure behavior after eight cycles with eight slugs (Figure 2d) for example, whose each gel slug volume was 0.25 PV. With the number of gel slug increasing, the breakthrough pressure gradient and the stable pressure gradient rose step by step. It's worth noting that before the fourth slug, the increase of brine flooding pressure was small with the number of gel slug increasing. It is considered that the weak gel injection amount was less than 1.0 PV, not enough to full the fracture. The weak gel controlled the seepage channel of fracture mainly through the patterns of entering, filling and retention, so the intensity of weak gel in the fracture was low. After four gel slugs were extruded, the pressure gradient rose more steeply and kept rising until the eighth slug. Even though the weak gel injection volume had exceeded the fracture volume, but the stranded gel was extruded and compacted during the subsequent slug and brine flooding, therefore the strength of gel in the fracture was more and more big. The visual record of the plugging process by eight cycles with eight gel slugs (Figure 3) revealed the rule above.

 

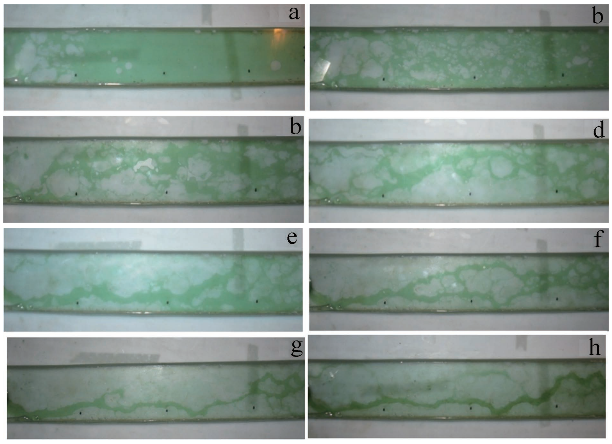


**Figure 3**
**Gel Distribution in the Fracture After Each Cycle of Brine Flooding (Eight Cycles With Eight Gel Slugs), and the Eight Conditions Were Shown in (a) First Cycle; (b) Second Cycle; (c) Third Cycle; (d) Fourth Cycle; (e) Fifth Cycle; (f) Sixth Cycle; (g) Seventh Cycle; (h) Eighth Cycle**

Figure 3 displays that the gel distribution in the simulation model after each cycle of brine flooding, as the brine was dyed deep color and the white was weak gel. After injection 1-2 slug, the weak gel was broken through by the follow-up brine and the presented shattered net shape, scattered in the fracture, with low intensity, part of which was drove forward by brine. After injection 3-4 gel slug, the area broken through by brine had presented characteristics of a big channel associated with many small throats. The intensity of weak gel was still low, part of them was drove forward, but the migration amount reduced obviously compared with that after 1-2 slug. After injection 5-6 gel slug, it was observed that the big channel formed previously was filled by follow-up gel gradually, and the area broken through by brine became a very narrow passage. The intensity of weak gel increased significantly, and most of them was not affected by brine flooding. After injection 7-8 gel slug, the intensity of weak gel was high enough, and the area broken through by brine narrowed further. The weak gel behavior of assembling, extrusion, and compaction in the fracture led to the rising pressure, which was consistent with the pressure gradient curve in Figure 2d.

## 3. PROFILE CONTROL RULE OF MULTI-CYCLE GEL INJECTION IN MULTIPLE FRACTURES SYSTEM

Figure 4 shows that the distribution of gel in the fractures (the widths of Model No. 2, Model No. 4 and Model No. 7 are respectively 80 μm, 150 μm, 330 μm) after each cycle brine flooding (the color refers to the instruction above). In the beginning, the fractures were filled with green brine. When the first gel slug was injected, it entered into the widest fracture first, which was plugged temporarily. The subsequent slugs entered into medium fracture and the narrowest fracture in turn (Figure 4c, Figure 4d), at this moment, weak gel existed in all the fractures. During the next cycle of brine flooding, the weak gel in the widest fracture was broken through, so the following gel slug entered into the widest fracture, and the percolation resistance of the widest fracture increased, when it was exceeded by the one of medium fracture or the narrowest fracture, the brine entered into the fracture with small percolation resistance. In the following cycles, the weak gel in a certain fracture was broken through, and the next gel slug entered into the fracture, gradually, the percolation resistance different between the three fractures was reduced (Figure 4e, Figure 4f). Ultimately, through gel injection by multi-cycle with small slug, the profile control effect in the multiple fractures system with different width was achieved.

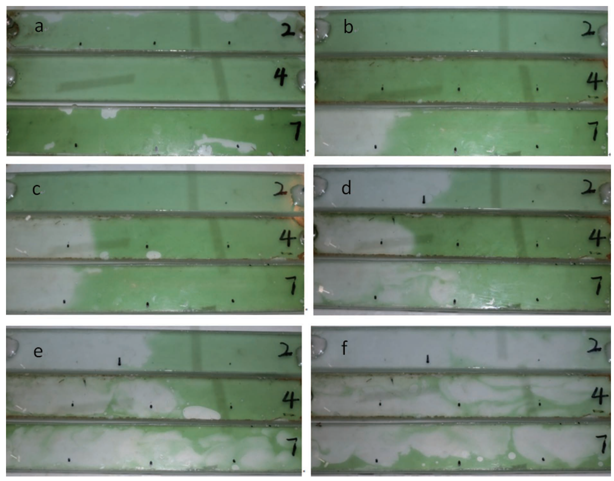


**Figure 4**
**Gel Distribution in the Fractures After Each Cycle Brine Flooding, and the Six Stages Were Shown in (a) Original State; (b) First Cycle; (c) Second Cycle; (d) Fourth Cycle; (e) Sixth Cycle; (f) Eighth Cycle**

Figure 5 shows that the stable pressure gradient in the multiple fractures system after each cycle of brine flooding by gel injection of multi-cycle and multi-slug. The steady pressure behavior in the multiple fractures system could be divided into three stages. The first was the stage of weak gel selective entrance (1-3 slugs), in this stage, the steady pressure was very low, and it increased slightly until the weak gel entered into all the fractures, which also shows that for the fractured formation with different width, water breakthrough would not be improved obviously by injecting only one or two gel slugs; the second was the stage of weak gel filling (3-8 slugs), in this stage, the steady pressure increased slowly, the weak gel filled the seepage channel broken through during brine flooding in the fractures step by step; the third was the stage of weak gel compaction (8-10 slugs), in this stage, the weak gel was extruded and compacted during brine flooding, and the gel with high intensity in the fractures was formed, eventually the steady pressure increased rapidly, which was consistent with the pressure gradient curve in Figure 4.

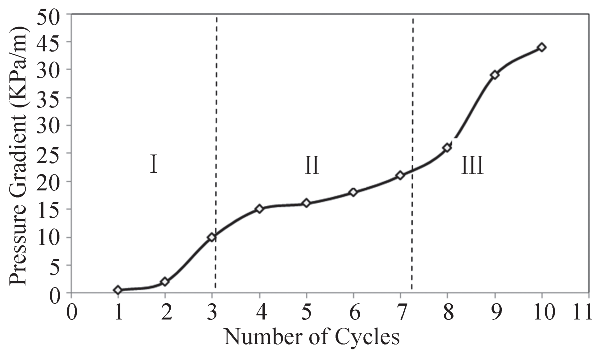


**Figure 5**
**Stable Pressure Gradient After Each Cycle of Brine Flooding by Gel Injection of Multi-Cycle and Multi-Slug**

Based on the above analyses, when injected continuously with big slug, the weak gel entered first into the widest fracture until filling under stressed, while only a few even no weak gel entered into the other fractures. Therefore, during the following brine flooding, the brine fingered along with the other fractures, resulted in bad profile control effect. When the weak gel was injected with multi-cycle and small slug, the gel would entered into secondary fractures after entering into the widest one. The percolation resistance different between fractures gradually diminished, and the overall pressure gradient of formation increased, as well as the water flooding swept area and oil recovery.

## CONCLUSION

(a) The plugging experimental results of multi-slug weak gel in single fracture and multiple fracture system illustrates that the brine flooding pressure after injecting gel by multi-cycle with small slugs, under the condition of the same gel volume, was much higher than that after continue injection. For the fractured reservoir to increasing oil production and decreasing water cut, the gel injection mode of multi-cycle with small slugs was the first priority.

(b) The process of multi-slug weak gel profile control in single fracture has two stages: gel filling stage and gel compaction stage; the process of multi-slug weak gel profile control in multiple fractures system has three stages: Gel selectively entrance stage, gel filling stage and gel compaction stage, while there would be no gel compaction stage, even no gel filling stage during the process of single cycle gel plugging in multiple fractures system.

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