Visible study of water shutoff techniques for reservoirs with high permeability channels

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Abstract. This paper describes a compound-linking gel system consisting of Polymer, Chromium (+3), Phenolic resin and rubber particles, which has good performance for water blocking. Indoor experiments demonstrate that the breaking through pressure of compound gel system is 4.92 MPa/m, which is much higher than 2.5-3 MPa/m of conventional, and its flooding resistance is better. The pressure of sand-pack with compound gel system reaches stability at 2.5MPa after 7PV water flooding while others stay at 1.1-1.6 MPa after 3-4PV water displacement. Visible flooding models are developed to optimize the injection volume and investigate the best location to deploy plugging agents. The results show that there is a limit on injection volume, and when it equals to 0.1-0.2 PV, the application may have economic success. For models with worm-shaped channels, the best location for plugging agents is just after “inflection point” near injecting well, which can make full use of the fluid diverting to achieve highest oil recovery.

1. Introduction

In China, many oilfields have stepped into the late development stage, where “fingering” of injected water becomes a common problem due to the reservoir heterogeneity [1, 2]. A recent survey indicated that the amount of water-intake in high permeability zone would account for 90% of total injected if the permeability ratio reached 5, which seriously impacts the economics and recovery [3].

Cross-linked polymer gels are currently used in profiling and water plugging application [4–6]. One choice is chromium (+3) cross-linked polymer gels, cross-linking mechanism of which is the complexation of Cr (+3) ions with carboxylate groups on the polymer chains [4-5]. Another commonly used gel system is phenol/formaldehyde cross-linker system [6-7]. The cross-linking mechanism involves hydroxymethylation of the amide nitrogen, with the subsequent propagation of cross-linking by multiple alkylation on the phenolic ring. Reddy et al [8] described an environmentally-preferable cross-linker to produce gel. Dai [9] et al had a lab experiments and developed gel foam water-plugging system aiming at the severe water production in the East China Sea Gas Field. The effectiveness of polymer gel is obvious; however, its strength, stability and washing resistance are still the challenges. In addition, few scholars had systematically research on the best position to deploy plugging agents.

In this paper, a compound cross-linked gel system is introduced, which consists of Polymer, Chromium, and Phenolic resin and rubber particles. The compound gel system has better strength,
stability and washing resistance. Also, visible plate models are designed to study the relationship between blocking effects and position to deploy plugging agents.

2. Experimental section

2.1. Chemical and fluids

The following chemicals were used in this study: Polymer (Dongying Guangzheng Products, molecular weight 15-18 million); Water-soluble phenolic resin (Wuhan Dahua Products, Content 99%); Organic Chromium cross-linker (Panjin Dongmeng Products, Content 40%); Rubber particles (diameter 0.25mm --0.3mm)

The oil this study used comes from Gudong reservoir (Shengli oilfield). The API of oil is 24 and its viscosity is 245 mPa·s at 60 °C (the experimental temperature). All solution is prepared by simulated formation water, whose salinity is 6778 mg/L.

2.2. Gel system formulation optimization

Strength is an important index of gel system properties. Figure 1 shows the “vacuum pressure breaking through” method to evaluate the gel strength [10]. The measuring procedure was shown as follows: 1) Link the colorimetric tube and measuring device with U-tube and rubber horse; 2) Locate U-tube end at 1-2 CM below the gel surface; 3) Start vacuum pump and boost slowly; 4) Record the maximal number on the gauge as breaking through vacuum (BV) pressure when the air breaks through the gel; 5) Each gel sample is measured three times and average the numbers as the final BV.

![Figure 1. Measuring equipment of vacuum pressure breakthrough.](image)

In this study, the influence factors of strength of compound gel system were discussed in detail, including concentration of Polymer, Chromium, and Phenolic resin and rubber particles. The optimal formulation was determined by orthogonal experiments. All of these tests were conducted at 60°C. The parameters and results of different tests are shown in Table 1.
Table 1. Orthogonal experiment of compound cross-linking gel system optimization.

| No. | Polymer, ppm | Chromium, % | Phenolic resin, % | Rubber particle, % | BV pressure, MPa |
|-----|--------------|-------------|-------------------|-------------------|------------------|
| 1   | 2000         | 0.01        | 0.225             | 0.02              | 0.034            |
| 2   | 2000         | 0.02        | 0.45              | 0.04              | 0.056            |
| 3   | 2000         | 0.04        | 0.675             | 0.06              | 0.061            |
| 4   | 2000         | 0.06        | 0.9               | 0.08              | 0.065            |
| 5   | 3000         | 0.01        | 0.45              | 0.06              | 0.065            |
| 6   | 3000         | 0.02        | 0.9               | 0.08              | 0.076            |
| 7   | 3000         | 0.04        | 0.675             | 0.02              | 0.075            |
| 8   | 3000         | 0.06        | 0.225             | 0.04              | 0.052            |
| 9   | 4000         | 0.01        | 0.675             | 0.06              | 0.09             |
| 10  | 4000         | 0.02        | 0.9               | 0.08              | 0.088            |
| 11  | 4000         | 0.04        | 0.225             | 0.02              | 0.072            |
| 12  | 4000         | 0.06        | 0.45              | 0.04              | 0.074            |
| 13  | 5000         | 0.01        | 0.9               | 0.02              | 0.078            |
| 14  | 5000         | 0.02        | 0.675             | 0.06              | 0.074            |
| 15  | 5000         | 0.04        | 0.225             | 0.08              | 0.084            |
| 16  | 5000         | 0.06        | 0.9               | 0.06              | 0.084            |

2.3. Evaluation of plugging performance

In order to investigate the plugging performance of gel system, a series of sand-pack flooding tests were done. A core holder of 1 in. (2.54 cm) in diameter and 1.8 ft (45 cm) in length was used for the sand-pack. Fresh quartz sand of different mesh was packed to get different permeability cores [11]. The cores were packed as follows [12]: the core holder, which was filled with formation brine, was positioned vertically and the quartz sand was added to fill it in 10 steps. In each step after sand was packed, the core holder was vibrated for 5 minutes. The evaluation experiments were conducted as the following procedures: Step 1: Evacuate the core and saturate with formation water. Step 2: Sand-pack core is water-flooded at the rate of 0.3 mL/min until the pressure reached stability, and the permeability \(k_b\) of the sand-pack core is calculated. Step 3: 0.15PV chemical slugs were injected and gelling 24 hours at 60 °C conditions. Step 4: Restart water-flooding at 0.3 mL/min rate and get the results of displacement pressure versus PV. The maximal value during flooding is the breaking through pressure. Step 5: Measure the permeability \(k_a\) of core after plugging when the pressure reached stability and get the plugging efficiency: \(E = \frac{k_b - k_a}{k_b} \times 100\%\).

The results of experiments are shown in Table 2.

Table 2. Sand-pack flooding tests for plugging performance.

| No. | Initial Permeability /10^3 μm^2 | Permeability after plugging /10^3 μm^2 | Plugging efficiency, % | Breakthrough Pressure (MPa/m) | Agents |
|-----|---------------------------------|---------------------------------------|------------------------|-------------------------------|--------|
| 1   | 632                             | 38.2                                  | 94.0                   | 2.53                          | 0.4% P+0.01%Cr |
| 2   | 601                             | 35.1                                  | 94.2                   | 2.70                          | 0.4% P+0.67%Pr |
| 3   | 625                             | 9.6                                   | 98.5                   | 3.03                          | 0.4% P+0.01%Cr+0.67%Pr+0.08%R |
| 4   | 613                             | 7.9                                   | 98.7                   | 4.92                          | 0.4% P+0.01%Cr+0.67%Pr+0.08%R |

(For the agents, P= Polyer, Cr=Chromium, Pr= Phenolic resin, and R=Rubber particles)

2.4. Micro flooding models

Two ideal porous micro-models are prepared by cementing quartz on glass plate with epoxy resins [13]. This paper used the conventional channel model to optimize the injection volume of gels and the position to deploy plugging agents, while the worm-shaped channel is used to simulate reservoir conditions. The general procedure is as follows: (1) Clean micro-models with laboratory cleaner. (2) The models are saturated with oil and then dry in an oven at 60 °C 24 hours. (3)0.05-0.4PV Plugging agents are injected.
at certain position of channel. (4) The subsequent water displacement was conducted until oil production became negligible (water cut >95%). (5) The sweep efficiency was calculated through “Grid-Box-Counting” method. The flooding tests were carried out at 60°C.

3. Results and discussion

3.1. Compound cross-linked gel system performance

The optimized compound gel formulation consisted of 4000 ppm polymer, 0.01% Chromium, 0.675% Phenolic resin and 0.08% Rubber particles. Figure 2 shows that, all the agents have good plugging efficiency. The breaking through pressure of sand-pack No.4 with the optimized gel formulation is 4.92 MPa/m, much higher than others. The pressure of sand-pack No.4 reaches stability after 7PV water flooding, while the others only 3-4PV.

![Plugging efficiency and breaking through pressure](image1)
![Washing resistance](image2)

**Figure 2.** Plugging performance of different agents.

3.2. Optimization of the amount of plugging agents

Generally, the larger amount of blocking agents applied, the more effective plugging performance can be gained, and diversion are more likely to occur for long-term water-flooding. Experiments performed in micro-models investigated the relation between sweep efficiency and the amount of plugging agent, as Figure 3 shows.

![Flooding models of different volumes of plugging agents](image3)

**Figure 3.** Flooding models of different volumes of plugging agents.

As Figure 4 shows, the sweep efficiency increases quickly with the injected PV at early stage and becomes gentle afterwards and the optimal scope is 0.1-0.2 PV.
3.3. Optimization of position to deploy plugging agents

3.3.1. Conventional channel models. Observation of Figure 5 and Figure 6 shows that diversion appears when the water front reaches blocking agents, however, water returns to the channels quickly after bypassing. The “wide and long” swept zone formed at the deploying position of 1/2 channel length distance to the injection well, nearly 50% sweep efficiency.

3.3.2 Worm-shaped channels models. Worm-shaped channels models are developed to simulate reservoir characteristics with 2 "inflection points" are located near the injection and production wells respectively. Five deploying positions are designed (front of the inflection point near injection well, at inflection point near injection well, behind of the inflection point near injection well, middle place of channel and front of the inflection point near production well). These experiments demonstrate that there is significant disparity in terms of oil recovery for different deploying positions. The case of location...
after the “inflection point” near injection well where agents are deployed has highest oil recovery, as Figure 7 shows.

![Figure 7](image)

**Figure 7.** Relationship of recovery and different deploying positions with 0.15PV agents slug for worm-shaped models.

4. Conclusion
The optimized compound-linked gel formulation has good plugging performance with higher breaking through pressure and flooding-resistance than conventional gel system. 0.1-0.2 PV is the best scope with respect of the amount of agents injected.

For conventional channel models, the deploying position of 1/2 channel length distance to the injection well has largest swept efficiency. For worm-shaped channels, blocking agents should be positioned at the location just after the “inflection point” near injection well in order to achieve highest recovery.

5. Notes
The authors declare no competing financial interest.

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