Study on seepage characteristics of Cr$^{3+}$ polymer gel and its mechanism- taken M oilfield in Changqing as an example

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Abstract. Cr$^{3+}$ polymer gel has strong salt tolerance, retention capacity and reservoir adaptability. This technology has obtained a significant effect of oil increasing, and the economic benefits was good. In order to meet the demand of improving oil recovery of M oilfield in Changqing, Seepage characteristics of Cr$^{3+}$ polymer gel and its mechanism were carried out. Results showed that when the polymer concentration of polymer and Cr$^{3+}$ polymer gel were the same, viscosity and molecules aggregates diameter of them were basic the same, but the resistance coefficient and residual resistance coefficient of Cr$^{3+}$ polymer gel was larger. It could be explained that the retention ability of Cr$^{3+}$ polymer gel was stronger. With the increase of relative molecular weight of polymer, the resistance coefficient and residual resistance coefficient of polymer and polymer gel also increased. When core permeability increased, the resistance coefficient and residual resistance coefficient decreased. Compared with polymer solution, Cr$^{3+}$ polymer gel had higher resistance coefficient and residual resistance coefficient, and residual resistance coefficient was larger than resistance coefficient. The mechanism study showed that water dilution in subsequent water flooding stage would cause molecular chain expansion in polymer gel, which caused the diameter of polymer gel molecular aggregates and retention in pores increasing.

1. Introduction
When adding crosslinking agents into polymer solution, crosslinking reaction will affect, and form polymer gel system. When the polymer concentration is low, polymer linears first become polymer clusters, and then the clusters gradually form a semi-fluid with integrity and flowability, which is called polymer weak gel [1]. The weak polymer gel system has been widely studied and applied in the oilfield for profile control.

In China, polymer gel technology began in the late 1960s. The field experiment of polymer gel was started in the 1970s, which has made the gel enter a new stage of development [2]. In the 1980s, polymer gel technology has made further progress, and many new types have been developed. The polymer gel system is more serialized and diversified [3]. In the 1990s, polymer gel technology was further studied, and it was more systematic and comprehensive [4]. Since the 21st century, fractal structure, fractal theory, weak gel, colloidal dispersion gel technology, characterization method of colloidal dispersion gel, formation and structure of colloidal dispersion gel have become research hotspots [5,6]. In recent years, research institutions, such as Petrochina research institute of exploration and development, institute of seepage fluid mechanics, Northeast petroleum university and Southwest petroleum
university, have carried out extensive research on polymer gel flooding technology, and made varying degrees of progress in system formulation and mechanism [7,8]. Many oilfields, such as Daqing, Shengli, Zhongyuan, Huabei and Dagang in China, have carried out field tests and obtained good results [9,10]. Both theoretical research and field test show that polymer gel flooding technology is a new technology with economic feasibility, simple technology and strong operability.

To meet the technical requirements for enhanced oil recovery in the target reservoir, in this paper, geological and fluid conditions of M high salinity reservoir in Changqing are studied, polymer viscosity, molecular aggregates, microstructure, seepage characteristics and mechanism were studied, and the method to improve polymer solution retention and liquid flow direction ability in high salinity reservoir was put forward, which provided the theoretical basis for the technical decision of enhanced recovery in the mine.

2. Materials and Methods

2.1. Materials
Polymer was partially hydrolyzed polyacrylamide (HPAM) produced by Shandong Noel biotechnology co. LTD, with molecular weight of $1300\times10^4$, $1700\times10^4$ and $2500\times10^4$, and solid content of 88%. Organic chromium was developed by northeast petroleum university, and the effective content of $\text{Cr}^{3+}$ was 2.7%. Experimental water was injection water from M oilfield in Changqing, and water quality analysis was shown in Table 1.

| Water type       | K$^+$+Na$^+$ | Ca$^{2+}$ | Mg$^{2+}$ | Cl$^-$ | SO$_4^{2-}$ | CO$_3^{2-}$ | HCO$_3^-$ | Total salinity (mg/L) |
|------------------|-------------|-----------|-----------|--------|-------------|-------------|-----------|-----------------------|
| Injected water   | 5270.0      | 380.0     | 99.0      | 4140.0 | 6185.3      | 49.9        | 776.7     | 16810                 |

Artificial cores, which are made up of quartz sands cemented with epoxy resin, were also utilized [11-13]. The cores were made up of quartz sands cemented with epoxy resin with permeabilities ($K_g$) of $0.1 \, \mu m^2$, $0.2 \, \mu m^2$, $0.8 \, \mu m^2$ and $1 \, \mu m^2$. Core diameter was 2.5 cm and length was 10 cm.

2.2. Apparatus
The viscosity of polymer solution and $\text{Cr}^{3+}$ polymer gel was measured by a DV-II Brookfield Viscometer under the temperature of 50°C. Rotor No. 0 was used for measurement, and the speed was set to 6 rpm/min. The microstructure of the polymer molecular aggregation was investigated under a Scanning Electron Microscope (S-3400N, Hitachi). The diameter of polymer molecular aggregation was measured by a Light Scattering System (BI-200SM, American Brookhaven). The main equipment used for the seepage characteristic experiments included an advection pump, a pressure sensor, a core handler, a hand pump, and a middle container. All the equipment, except the advection pump and the hand pump, remained at room temperature, whereas the others were put in a thermostat oven at 50°C.

2.3. Methods
Step 1, the dried cores were weighed before and after being saturated with water at room temperature, and pore volume (PV) and porosity were calculated according to the weight difference. Step 2, water was also injected until the pressure becomes constant, and recorded the injected pressure ($P_1$). Step 3, polymer solution and polymer gel (PV = 5) were inserted into the core, and recorded the injected pressure ($P_2$). Step 4, water was injected until the pressure becomes constant, and recorded the injected pressure ($P_3$).

The injection rate was 0.3mL/min, and calculated the resistance coefficient and residual resistance coefficient.

3. Results

3.1. Properties of polymer solution and its influencing factors
3.1.1 Viscosity of polymer. Polymer solutions (M=1300×10⁴, 1700×10⁴ and 2500×10⁴) were prepared by injecting water. The experimental results of relationship between viscosity and polymer concentration were shown in Table 2.

Table 2. Viscosity of different polymer molecule weight and concentration (mPa·s).

| Polymer molecule weight | Polymer concentration (mg/L) | Viscosity increased rate (%) |
|------------------------|------------------------------|-----------------------------|
|                        | 600             | 800           | 1000         | 1200         | 1600         |
| 1300×10⁴               | 6.5             | 8.2           | 11.5         | 17.6         | 32.1         | 393.8        |
| 1700×10⁴               | 7.2             | 11.9          | 16.3         | 23.2         | 38.8         | 438.9        |
| 2500×10⁴               | 8.5             | 14.2          | 20.5         | 27.7         | 45.3         | 432.9        |

As can be seen from Table 2, the viscosity of polymer solution increased with the increasing of polymer concentration and molecular weight. Among the three kinds of polymer, molecule weight of 1700×10⁴ had a better viscosity increased rate.

3.1.2 Viscosity of polymer gel. Polymer solutions (M=1300×10⁴, 1700×10⁴ and 2500×10⁴) were prepared by injecting water with concentration of 600mg/L, 800mg/L, 1000mg/L, 1200mg/L and 1600mg/L, respectively. Crosslinking agent was added into polymer solution with ratio of "polymer: Cr³⁺=90: 1". Viscosities of Cr³⁺ polymer gel at different time were shown in Figure 1.

Figure 1. Relationship between viscosity and time of polymer with different polymer molecular weight.

![Figure 1](attachment:image1.png)

Figure 1 showed that the viscosity of polymer gels changed little with time. The results indicated that the "intramolecular" cross-linking reaction may occur in polymer gel. However, the viscosity could not be used as an evaluation index to determine cross-linking reaction of "intramolecular". It was necessary to measure the residual resistance coefficient and resistance coefficient in seepage characteristic experiments.

3.1.3 Diameter of polymer and Cr³⁺ polymer gel molecular aggregates. Polymer solutions (M=1300×10⁴, 1700×10⁴ and 2500×10⁴) were prepared by injecting water with concentration of 1000mg/L. A part of polymer was diluted to 50mg/L, 100mg/L and 200mg/L, respectively. Another part added crosslinking agent according to the ratio of "polymer: Cr³⁺=90: 1", and then polymer gel was diluted 50mg/L, 100mg/L and 200mg/L, respectively. Table 3 showed the diameter of polymer and polymer gel molecular aggregates.

Table 3. Molecular aggregate diameter of polymer and polymer gel with different polymer molecule weight and concentration.

| Polymer molecule weight (nm) | Polymer concentration (mg/L) | 50      | 100     | 150     |
|------------------------------|------------------------------|---------|---------|---------|
| Polymer                      | 1300×10⁴                    | 118.6±1.62 | 139.4±1.13 | 168.8±1.22 |
|                  | 1700×10⁴ | 167.6±1.56 | 183.7±0.98 | 214.9±0.89 |
|------------------|----------|------------|------------|------------|
| 2500×10⁴         | 222.1±0.96 | 240.3±1.16 | 275.1±1.34 |
| Polymer gel      | 1300×10⁴ | 115.9±1.36 | 127.4±1.11 | 167.6±0.63 |
| 1700×10⁴         | 164.8±1.15 | 181.5±0.88 | 211.6±1.78 |
| 2500×10⁴         | 218.6±1.08 | 237.0±1.02 | 272.9±1.29 |

Table 3 showed that the molecular aggregate diameter of polymer and polymer gel increased with the increased of polymer concentration and molecular weight. When polymer concentration exceeded 100mg/L, the molecular aggregate diameter began to increase significantly. Compared with the polymer solution, molecular aggregates diameter of polymer gel decreased slightly. This was because that the molecular aggregates of polymer gel presented a certain degree of shrinkage after the "intramolecular" cross-linking, which made molecular aggregates reduced slightly. Further analysis showed that when the polymer concentration exceeded 100mg/L, diameter of molecular aggregates increased significantly, which indicated that the intermolecular entanglement of polymer began to increase significantly (seen in Figure 2).

![Figure 2. SEM of molecular aggregates.](image)

3.2 Seepage characteristics of polymer solution and Cr³⁺ polymer and their influencing factors

3.2.1 Polymer solution. Polymer solutions (M=1300×10⁴, 1700×10⁴ and 2500×10⁴) were prepared by injecting water with concentration of 800mg/L. Resistance coefficient and residual resistance coefficient were shown in Table 4, and relationship between injection pressure and PV was shown in Figure 3.

Table 4. Resistance coefficient and residual resistance coefficient.

| Parameter                  | Polymer molecule weight |
|----------------------------|-------------------------|
|                            | 1300×10⁴ | 1300×10⁴ | 1300×10⁴ |
| Resistance coefficient     | 10.00     | 15.38     | 20.00     |
| Residual resistance coefficient | 1.67     | 2.69     | 3.60     |

![Figure 3. Relationship between injection pressure and PV number (Kg=800×10⁻³μm²)](image)
As can be seen from Table 4 and Figure 3, the resistance coefficient and residual resistance coefficient increased as the polymer molecular weight increased. Polymer retention in pores increased with the injection of polymer, and when the polymer injection was equal to the production, injection pressure tended to be stable. In subsequent water flooding stage, the seepage resistance and injection pressure decreased. When the retention of polymer in pore was no longer changed, seepage resistance and injection pressure unchanged.

### 3.2.2 Cr₃⁺ polymer gel.
Polymer solutions (M=1300×10⁴, 1700×10⁴ and 2500×10⁴) were prepared by injecting water with concentration of 800mg/L. The crosslinking agent was added according to the ratio of "polymer: Cr³⁺"=”90: 1". Resistance coefficient and residual resistance coefficient were shown in Table 5, and relationship between injection pressure and PV was shown in Figure 4.

#### Table 5. Resistance coefficient and residual resistance coefficient.

| Parameter                  | Polymer molecule weight |
|----------------------------|-------------------------|
|                            | 1300×10⁴    | 1300×10⁴    | 1300×10⁴    |
| Permeability(×10⁻³μm²)     | 101         | 227         | 412         |
| Resistance coefficient     | 73.25       | 57.27       | 53.30       |
| Residual resistance coeff. | 53.00       | 39.09       | 36.00       |

As can be seen from Table 5 and Figure 4, contrary to the polymer solution (Table 4), residual resistance coefficient of polymer gel was greater than resistance coefficient, which showed unique seepage characteristic and a better liquid flow direction.

#### Figure 4. Relationship between injection pressure and PV number of polymer gel with different polymer molecular.

(a) M=1300×10⁴  (b) M=1300×10⁴  (c) M=1300×10⁴

### 4. Conclusions

Under the condition of the same polymer concentration, viscosity and polymer molecular aggregates of polymer solution and Cr³⁺ polymer gel were basically the same, but the resistance coefficient and residual resistance coefficient of the latter were larger, indicating the existence of "intramolecular" cross-linked in the Cr³⁺ polymer gel. With the increase of relative molecular weight of the polymer, the resistance coefficient and residual resistance coefficient of Cr³⁺ polymer gel and polymer solution increase. With the increase of core permeability, the resistance coefficient and residual resistance coefficient of Cr³⁺ polymer gel and polymer solution decrease. Compared with polymer solution, Cr³⁺ polymer gel had higher resistance coefficient and residual resistance coefficient, and the residual resistance coefficient was larger than resistance coefficient, which showed a better fluid diversion ability.

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