Research on Variation Law and Prediction Model of Working Viscosity of Salt Resistant Polymer

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Abstract. Using seepage experiments and theoretical methods, the effects of injection fluid viscosity and injection speed on the change of working viscosity of salt-resistant polymers in porous media with different permeability are studied. And developed a working viscosity prediction model. The results show that as the permeability and viscosity of the injection fluid increase, the working viscosity of the salt-resistant polymer in the porous medium increases; as the injection speed increases, the polymer exhibits viscoelasticity, and the working viscosity decreases first and then increases; under the same conditions, the working viscosity of the salt-resistant polymer is higher than that of the ordinary polymer; in the gray correlation analysis, the correlation coefficient of the injection fluid viscosity and working viscosity is 0.958, the permeability is 0.954, and the injection speed is 0.709; a multivariate statistical regression method is used to give a prediction model for the working viscosity of salt-resistant polymers. The average deviation between the predicted value and the actual calculated value is only 4.40%.

1. Introduction
At present, polymer flooding technology has become a key technology for the continuous development of oil fields. Polymer is one of the most important oil displacement agents for EOR [1-3]. The main oil displacement mechanism is to increase the range of displacement through viscosity increase, effectively suppress the fingering phenomenon, and significantly reduce the mobility ratio. The effective working viscosity of the polymer in the formation is the key factor affecting the effect of controlling the mobility, but the commonly used polymer is partially hydrolyzed polyacrylamide, which is greatly affected by the shearing effect and salinity of the formation. The viscosity retention rate is low and the stability is poor [4-6]. Therefore, salt-resistant polymers have been developed, which are mainly divided into ultra-high molecular weight HPAM, amphoteric polymers, temperature and salt-resistant monomer copolymers, hydrophobic association polymers, multi-component combination copolymers, comb polymers, etc [7]. Sun Gang et al. Studied the synthesis and application of new salt-resistant polymers. The viscosity-increasing, salt-resistance and aging stability of salt-resistant polymers are superior to ordinary polymers. At the same dosage, physical simulation experiments can increase recovery The rate is 4.5% [8]. Xie Kun et al. Studied the suitability and mechanism of the reservoir. When changing the spatial
configuration of the polymer molecular aggregation to increase the viscosity of the aqueous solution of salt-resistant polymers and evaluating the suitability of the reservoir, the viscosity index should not be paid too much attention, but pay attention to the adaptability between its molecular aggregates and heterogeneous reservoirs [9]. Wenzhe Chen et al. discussed the development progress and performance evaluation of salt-resistant polymers and pointed out the development direction of chemical flooding polymers [10]. Zhenbin Chen et al. evaluated the effect of composite brine on the rheology of salt-resistant polymers and characterized the structure of the salt-resistant polymers by infrared spectroscopy.

None of the above studies described the factors affecting the working viscosity of the salt-resistant polymer in the core and the study of the working viscosity prediction model. This paper studies the influence factors of core permeability, injection fluid viscosity and injection speed on the working viscosity of the anti-salt polymer, compares and analyzes the changes in working viscosity of ordinary polymer and salt-resistant polymer under different conditions, and uses gray correlation analysis to study different factors. The correlation between the working viscosity and the calculation results of the salt-resistant polymer's working viscosity under different conditions uses a multivariate statistical regression method to obtain a salt-resistant polymer's working viscosity prediction model. It has a guiding significance for field application.

2. Experiment

2.1. Materials
Polymer: ordinary polymer, relative molecular weight $800 \times 10^4$, effective content and 90%, DS800 salt resistant polymer, relative molecular weight $800 \times 10^4$, effective content and 90%;
Experimental water: NaCl content is 4500mg/L, all filtered through 0.45μm filter membrane before use; Experimental core: natural beret core, the core size is $2.5\text{cm} \times 10\text{cm}$, and the effective permeability $K_w$ is in the range of $50~150 \times 10^{-3} \text{μm}^2$;
Experimental instruments: a set of core displacement systems such as thermostat, ISCO pump, core holder, intermediate container, precision pressure gauge, filtration device, HAKE rheometer, and confining pressure pump.

2.2. Procedure
(1) Determine the core permeability and porosity and other parameters, and place the core in the incubator for more than 8h after evacuating and saturating the formation water;
(2) Assemble the experimental process, put the core into the core holder and empty the air;
(3) Inject water at a constant flow rate until the pressure at both ends of the core is stable. Increase the injection rate until the pressure at both ends of the core is stable. Repeat the above steps to measure the permeability of the core;
(4) Inject simulated water at a constant flow rate until the pressure at both ends of the core is stable; then inject polymer solution 3 ~ 5PV until the pressure at both ends of the core is stable, record the pressure and flow at both ends of the core, then gradually increase the injection speed and record it again until all the experimental points are measured;
(5) According to the experimental data, calculate the residual resistance factor and the working viscosity of the polymer solution in the porous medium.

2.3. Plan
The injection fluid viscosity is 20, 40, 60 mPa·s, the seepage experiment is carried out in the core with the effective permeability of 53, 105, 154mD. When studying the effect of injection speed on the working viscosity of the polymer, The displacement rate is 2, 16, 32, 64ml/h. the displacement rate is 6ml / h for other experiments.
3. Results and analysis

3.1. Working viscosity calculation

During the seepage process, the polymer is sheared by the pore medium, and the working viscosity is lower than the apparent viscosity. The shearing effect of the polymer solution is related to the injection rate on the one hand, and the permeability of the porous medium during the polymer flooding process on the other hand. During the displacement process, a part of the polymer will form adsorption and retention on the inner surface of the rock or the tiny pores, resulting in the change of the shear rate of the polymer solution. Calculation formula of working viscosity of polymer solution:

$$\mu_p = \frac{K_w}{R'_{kk}} \times \frac{\Delta P A}{QL} \quad (1)$$

In the formula: $R'_{kk}$ - (pseudo) residual resistance factor, (pseudo-residual resistance when the adsorption retention is not saturated, and residual resistance when the adsorption retention is saturated); $K_w$ - water phase permeability before polymer injection, $\mu$ m$^2$; $Q$ - flow, cm$^3$/min; $L$ - core length, m; $\Delta P$ - pressure difference between two seepage sections, Pa; $A$ - core cross-sectional area, m$^2$.

3.2. Variation of working viscosity of salt-resistant polymers

3.2.1. Permeability.

Simulated water with a NaCl content of 4500 mg/L was used to prepare two polymers of the same viscosity (40 mPa·s), and seepage experiments were conducted in natural cores with different permeability (53, 105, 154 mD) according to the pressure collected during the experiment. Equal parameters combined with formula (1) calculate the working viscosity of the polymer in the porous medium, and the variation law is plotted as shown in Figure 1. It can be seen that as the permeability increases, the working viscosity of the polymer solution in the porous medium also increases. Under the same permeability condition, the working viscosity of DS800 salt-resistant polymer in the core is higher than that of ordinary polymer. This is because the salt-resistant polymer can form hydrophobic association between molecular chains under the same salinity. The addition of salt-resistant monomers guarantees its high viscosity retention rate, while ordinary polymers cannot form hydrophobic associations between molecular chains, and their ionic groups are weakly polar carboxylate anions, which are more shielded and resistant. The salinity is weak and the working viscosity is low. At the same time, the working viscosity is a parameter related to the shear rate. The smaller the permeability, the greater the shear rate. As the permeability increases, the polymer solution undergoes shearing and stretching during the migration in the porous medium. The effect becomes smaller and the displacement pressure difference becomes smaller. Therefore, the working viscosity of the polymer solution in the porous medium increases.

![Figure 1. Working viscosity changes with core permeability.](image-url)
3.2.2. Injection fluid viscosity. In a natural core with an effective permeability of 105 mD, a polymer solution with a viscosity of 4500 mg/L and a viscosity of 20, 40, and 60 mPa·s was used to conduct a seepage experiment to study the effect of the viscosity of the injection fluid on the working viscosity. Through the pressure and other parameters collected during the fluidity experiment, the working viscosity of the polymer solution in the porous medium is calculated according to formula (1). It can be seen from Figure 2 that in the same permeability core, the working viscosity of both polymers increases with the increase of the viscosity of the injection fluid. Under the conditions of the same salinity and the same viscosity, the working viscosity of the DS800 salt-resistant polymer is larger than ordinary polymers. This is mainly due to the introduction of hydrophobic monomers on the molecular chain of the salt-resistant polymer, intermolecular interactions can occur in the solution, the mutual entanglement between the molecular chains is more obvious. The formation of a supramolecular network structure is more stable, the hydrodynamic volume is increased, the shear resistance is stronger at the same permeability, the viscosity retention rate in the formation is high, and the pressure difference during displacement is greater, working viscosity is also greater.

![Figure 2. Working viscosity changes with injection fluid viscosity.](image_url)

3.2.3. Injection speed. Using simulated water with a NaCl content of 4500 mg/L to prepare two polymer solutions with a viscosity of 40 mPa·s, a seepage experiment experiment with different injection rates (2, 16, 32, 64 mL/h) was carried out in a core with a permeability of 105 mD. Study the influence of injection speed on working viscosity, as shown in Figure 3. As the injection rate increases, the working viscosity of the polymer solution decreases first and then increases. The working viscosity of the DS800 salt-resistant polymer is always higher than that of ordinary polymers. Because the polymer has both shear flow and tensile flow in the porous medium. Within a certain range of seepage velocity, the migration of polymer solution in porous media is mainly based on shear flow. The flow rate increases and the viscosity decreases. The fluid exhibits a pseudoplastic fluid characteristic. When the flow velocity exceeds a certain range, the stretching effect is enhanced, the stronger the entanglement of the polymer molecules, the greater the microscopic force generated during the seepage process, resulting in stronger viscoelasticity, the elastic effect of the polymer solution is greater than the viscous effect, and In view of the increase in injection speed and the increase in working viscosity, this increase is mainly due to elastic viscosity. Under the conditions of the same salinity and injection speed, the DS800 salt-resistant polymer molecular structure contains a salt-resistant monomer that is not easily hydrolyzed, which can make the polymer molecular chain stretch linearly in salt water. At the same time, it has better ability to deform via holes, and its working viscosity in porous media is higher than that of ordinary polymers.
3.3. Prediction model of working viscosity of salt-resistant polymer

3.3.1. Grey correlation analysis. In order to establish the numerical relationship between the salt-resistant polymer working viscosity and its influencing factors, it is necessary to use the grey correlation analysis method to calculate the correlation between each influencing factor and its working viscosity, select appropriate independent variables, and establish a linear regression model.

The working viscosity of salt-resistant polymers in the core is the result of a combination of factors, so consider establishing a multivariate linear analysis model. Two principles should be followed when choosing variables: 1. Explaining factors need to have a high correlation; 2. The principle of parameter saving should minimize the number of variables. In this experiment, the gray correlation analysis method was used to obtain the correlation between the polymer working viscosity and various factors, and to determine the independent variables of the regression equation.

This article uses Matlab software programming to calculate the gray correlation of various relevant factors. The specific calculation steps are as follows:

1. Determine the reference sequence and comparison sequence;
   Define the reference sequence to characterize the influence of other factors on the reference sequence; define the comparison sequence, all data sequences that affect the reference sequence.
2. Dimensionlessize the reference sequence and the comparison sequence;
3. Solve the gray correlation coefficient;

$$\zeta = \frac{a + \rho \ast b}{c + \rho \ast b}$$ \hspace{1cm} (2)

In the formula: a- the minimum value of the absolute value of the difference between the comparison sequence and the reference sequence; b- the maximum value of the absolute value of the difference between the reference sequence and the comparison sequence; \(\rho\)- resolution coefficient, this experiment takes 0.5.

4. Find the relevance \(r\).

The correlation coefficient is a coefficient that characterizes the correlation between the reference sequence and the comparison sequence, so it is not a fixed value, and there is more than one value. The correlation coefficient of each point needs to be averaged as an indicator of the degree of correlation between the reference sequence and the comparison sequence.

| Parameter                      | Correlation coefficient |
|-------------------------------|-------------------------|
| Injection fluid viscosity (mPa·s) | 0.958                   |
| Permeability (mD)             | 0.954                   |
| Injection rate (mL/h)         | 0.709                   |
It can be seen from Table 1 that the viscosity of the injection fluid and the core permeability have the highest correlation with the working viscosity of the salt-resistant polymer, with correlation coefficients of 0.958 and 0.954, respectively. It shows that the change of injection fluid viscosity and core permeability has the greatest impact on the working viscosity of DS800 salt-resistant polymer in the core, and the correlation coefficient of injection velocity is 0.709, indicating that the change of injection velocity has a lesser effect on the working viscosity of salt polymer than injection fluid and core permeability.

Therefore, when using multiple statistical regression analysis to predict the model, the core permeability, polymer injection viscosity and injection speed are selected as the comparison series, and the reference series is the salt-resistant polymer working viscosity.

### 3.3.2. Multiple statistical regression analysis

Multivariate statistical regression is an optimal linear regression method based on a statistical assumption based on least squares. It mainly studies the linear relationship between a dependent variable and multiple independent variables. This time, the working viscosity, polymer injection viscosity, core permeability and other related parameters at an injection rate of 6mL/h were used. Linear regression was performed using SPSS software to obtain the linear equations between different variables and passed various hypothesis tests. Substituting the original data for the deviation test, the average relative deviation between the working viscosity of the salt-resistant polymer and the fitting viscosity is less than 5%. It is considered that the regression equation can accurately describe the change of the working viscosity of the salt-resistant polymer in the core.

\[
\mu = c \cdot K + d \cdot \mu_0 + e \cdot v + f \tag{3}
\]

In the formula: \(\mu\)-viscosity of injection fluid, mPa·s; \(K\)-core effective permeability, mD; \(v\)-injection rate, ml/h.

**Table 2. DS800 working viscosity linear regression formula coefficient.**

| Parameter Coefficient | c   | d   | e   | f   |
|-----------------------|-----|-----|-----|-----|
| 0.006                 | 0.063 | 5.922 | 0.684 |

The salt-resistant polymer working viscosity prediction model given by multiple statistical regression is used to predict the working viscosity under different conditions, and the average deviation between the predicted value of the model and the actual calculated value is calculated, as shown in Table 3. The actual value and the predicted value were selected as the average value of the permeability and injection viscosity. Finally, the average deviation was calculated to be 4.40%, which meets the requirement of deviation control at 5%, indicating that the established salt-resistant polymer solution has a working viscosity in porous media. The prediction model is relatively accurate.

**Table 3. Working viscosity fitting.**

| Permeability (mD) | Injection viscosity (mPa·s) | Working viscosity (mPa·s) | Predicted value (mPa·s) | Deviation (%) |
|-------------------|----------------------------|---------------------------|-------------------------|---------------|
| 52.00             | 20.10                      | 3.63                      | 3.45                    | 5.05          |
| 55.70             | 40.10                      | 4.35                      | 4.67                    | 7.35          |
| 53.20             | 59.80                      | 6.10                      | 5.90                    | 3.35          |
| 103.00            | 19.90                      | 4.00                      | 4.04                    | 0.91          |
| 106.00            | 39.90                      | 4.85                      | 5.31                    | 9.57          |
| 95.90             | 59.90                      | 6.58                      | 6.51                    | 1.01          |
| 150.00            | 20.30                      | 4.74                      | 4.46                    | 5.87          |
| 152.00            | 40.30                      | 5.45                      | 5.73                    | 5.21          |
| 149.00            | 60.30                      | 7.15                      | 7.04                    | 1.61          |

Average deviation 4.40
4. Conclusion

(1) The working viscosity of the polymer solution increases as the permeability and the viscosity of the injection fluid increase.

(2) As the injection speed and shear rate increase, due to the effect of viscoelasticity, the working viscosity of the polymer tends to decrease first and then increase. Under the same conditions, the working viscosity of the salt-resistant polymer is higher than that of the ordinary polymer.

(3) Using the grey correlation analysis method, the correlation coefficient between the viscosity of the injection fluid and the working viscosity is 0.958, followed by the permeability of 0.954, the smallest correlation is the injection rate, and the correlation coefficient is 0.709.

(4) The prediction model of salt-resistant polymer working viscosity obtained by multivariate statistical regression analysis, by comparing the actual calculated value with the predicted value, the average deviation is 4.40%, which proves that the prediction model has good accuracy.

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References

[1] Zhang Xianbin, Li Xin, Chen Anliang, Chen Leixu, Chen Chengbin, He Peng, Fu Mingshun, Xie Binqiang. Preparation and Performance Evaluation of High Temperature Resistant Polymer Tackifier for Drilling Fluid [J]. Oil Field Chemistry, 2020, 37 (01): 1-6 + 16.

[2] Chen Lei, Bao Wenhui, Guo Bumin, Wang Xingzun, Li Meng, Sun Houtai. Performance evaluation of high temperature resistant seawater-based fracturing fluid thickener [J]. Oil Field Chemistry, 2020, 37 (01): 17-21 + 28.

[3] Guo Xuelei. Synthesis and evaluation of temperature- and salt-resistant emulsion polymer fluid loss control agent HT-PL [J]. Petrochemical Technology, 2019, 26 (11): 10-11 + 27.

[4] Dong Mingtao, Zhang Kangwei, Liu Gang, Liao Ruiquan, Li Zhen, Cheng Li. Preparation and performance evaluation of temperature- and salt-resistant polymer microsphere gel system [J]. Oilfield Chemistry, 2019, 36 (03): 405- 410.

[5] Wang Nannan. On the current status and development trend of temperature and salt resistance cross-linked polymer flooding technology [J]. Chemical Engineering and Equipment, 2019 (08): 47-48.

[6] Pan Feng. Preparation and performance evaluation of salt-tolerant polymers for oilfield wastewater preparation [J]. Science Technology and Engineering, 2019,19 (19): 111-117.

[7] Luo Feng. Evaluation of oil displacement effect of salt-resistant polymer and its field application [J]. Inner Mongolia Petrochemical Technology, 2019, 45 (06): 27-28.

[8] Sun Gang, Li Bo. Development and application of salt-tolerant polymers in Daqing Oilfield [J]. Daqing Petroleum Geology and Development, 2019, 38 (05): 265-271.

[9] Xie Kun, Lu Xiangguo, Jiang Weidong, Li Qiang. Adaptability of salt-resistant polymer reservoir and its mechanism of action [J]. Journal of China University of Petroleum (Natural Science Edition), 2017, 41 (03): 144-153.

[10] You Yi Zhu, Wen Li Luo, Guo Qing Jian, Chao An Wang, Qing Feng Hou, Jia Ling Niu. Development and Performance of Water Soluble Salt-Resistant Polymers for Chemical Flooding [J]. Advanced Materials Research, 2012, 1672.