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Contribution degree of fluidity control for polymer flooding in heavy oil reservoir

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Abstract: The unfavorable mobility ratio of heavy oil reservoirs makes the effect of polymer flooding poor. From the mechanism of polymer mobility control, the contribution of viscosity and residual resistance factor to the effect of oil displacement is analyzed to find the development direction of polymer flooding suitable for heavy oil reservoir. Firstly, the mathematical model of polymer flooding can be established to characterize the solution viscosity and residual resistance factor, and then the numerical solution is obtained. The corresponding contribution degree is analyzed by MATLAB using the grey correlation method. The results show that the contribution of the viscosity of the polymer solution to the injection pressure (75%) is significantly higher than the residual resistance factor (25%), but the contribution to the recovery (48%) is slightly lower than the residual resistance factor (52%). Under the conditions of limited injection pressure, the oil displacement system with low viscosity and high residual resistance factor is more beneficial to the mobility control of polymer flooding in heavy oil reservoirs.

1. Introduction

In the current polymer flooding test of heavy oil reservoirs, the polymer flooding enhanced oil recovery range is 5%~8%, and the unfavorable fluidity ratio of heavy oil reservoirs is significantly higher than polymer flooding control capacity [1]. The polymer for oil displacement mainly relies on the viscosity of the solution and the residual resistance coefficient to control the mobility, thus improving the oil displacement effect. Increasing the viscosity of the polymer solution is the primary method to improve the effect of polymer flooding [2]. However, on the one hand, the shearing effect during the injection process, thermal degradation [3] and the effect of water mineralization (mainly Ca^{2+}, Mg^{2+}) [4] greatly reduce the effective viscosity of the polymer solution in the ground; On the other hand, due to the influence of injection capacity, economic benefits and other factors, the working viscosity of the polymer solution is not likely to be infinite [5]. At present, the RRF of the most commonly used partially hydrolyzed polyacrylamide solution in oil fields is generally 1.0~3.0, and the ability to reduce the permeability of water phase is limited [6]; With the development of polymer synthesis, it is now possible to synthesize polymer with a high residual resistance coefficient [7-9]. Therefore, improving the residual resistance coefficient of the polymer solution and mobility control has become an important research direction.

Whether it is to increase the viscosity of the polymer solution or the residual resistance coefficient can improve the polymer flooding effect. Because of the different modes, the contribution of improving the displacement effect is also different. Therefore, it is necessary to numerically analyze the contribution of the increase of the residual resistance coefficient of the polymer to the oil displacement effect, and the contribution ratio between the viscosity of the polymer solution and the residual resistance coefficient, so as to further develop the polymer flooding technology.

2. Mathematical model of polymer flooding in layered heavy oil reservoirs

2.1 Basic assumption

The mathematical model of the polymer flooding of layered heavy oil reservoirs follows the following assumptions: (1)The longitudinal direction of the reservoir consists of three independent layers, interlayer channeling appear through introducing vertical permeability; (2) The polymer flooding process involves oil-water two-phase, and the polymer is present in the aqueous phase; (3) Rock, fluid is incompressible; (4) Extended Darcy's law is suitable for describing multiphase flows; (5) The polymer only affects the viscosity and relative permeability of the water phase and has no effect on the oil phase.

2.2 Mathematical model building

2.2.1 Fluid basic flow equation

The polymer flooding process involves three successive injection processes: water flooding, polymer injection and water flood. Thus, the polymer flooding model contains two phases and three components. Fluid basic flow equation follows mass conservation and Darcy's law.

(1) Continuity equation of oil, water and component polymers.

$$\begin{cases} -\nabla V_o + q_o = \dfrac{\partial}{\partial t}(\phi S_o) \\ -\nabla V_a + q_a = \dfrac{\partial}{\partial t}(\phi S_a) \\ -\nabla (C_{pa} \cdot V_a) + q_a \cdot C_{pa} = \dfrac{\partial (S_a C_{pa})}{\partial t}(\phi - \phi_{IPV}) + \dfrac{\phi \partial C_{ad}}{\partial t} \end{cases} \quad (1)$$

Equation：Φ—porosity；q_o、q_a—import and export residual oil, flow rate of water phase, mL；V_o、V_a—oil and water phase seepage velocity, mL/min；S_o、S_a—oil, water phase saturation; C_{pa}—polymer solution concentration, mg/L; C_{ad}—polymer adsorption concentration, mg/L；Φ_{IPV}—inaccessible porosity.

(2) Motion equation of oil and water two-phase.

$$\begin{cases} V_o = -\dfrac{K \cdot K_{ro}}{\mu_o} \nabla P_o \\ V_a = -\dfrac{K \cdot K_{ra}}{\mu_a R_k} \nabla P_a \end{cases} \quad (2)$$

Equation：K_{ro}、K_{ra}—oil-water relative permeability；R_k—permeability reduction factor；P_o、P_a—oil-water pressure，MPa；μ_o、μ_a—oil-water viscosity，mPa·s.

2.2.2 Equation of polymer solution characteristic

The establishment of equation of polymer characteristic is divided into the characteristic relationship between the viscosity of polymer solution and the coefficient of decline of permeability: ① The rheologic properties are characterized by the power law fluid properties that are basically satisfied by the oil-displacing polymer, and then the shear rheological feature model under porous media conditions is constructed through the equivalent steady shear rate in porous media is established by formula correction. Finally, considering that the performance of the polymer solution in the porous medium is the effective viscosity (the sum of the viscous viscosity and the elastic viscosity), the relationship between the apparent viscosity and the effective viscosity is established, so that can build the characteristic relationship of the viscosity of the polymer solution; ② A bivariate polynomial nonlinear regression method was used to establish the relationship between residual resistance coefficient and polymer concentration and flow rate.

2.2.2.1 Polymer solution viscosity

In laboratory experiments and mine applications, the polymer exists in the porous medium. Therefore, the viscosity of the polymer solution must be characterized by the rheological properties in the porous medium. The mathematical description is carried out in two steps: (1) Characterization based on the relationship between apparent viscosity of polymer solution building by the power law model, solution concentration and shear rate as follows [10] :

$$\begin{cases} \mu_v = K \times \gamma^{n-1} \\ K = a + bC_p + cC_p^{\ 2} \\ n = d + eC_p + fC_p^{\ 2} \end{cases} \tag{3}$$

Equation: μ_v—apparent viscosity of polymer solution, mPa·s; K—consistency coefficient, mPa·s^n; n—power law index; a、b、c、d、e、f—input parameters.

For power-law fluids, Hirasaki and Pope modify the Blake-Kozeny mode to derive the equivalent shear rate calculation formula for porous media [12].

$$\begin{cases} \gamma = \dfrac{3.97 \cdot C \cdot \sqrt{v_{ax}^{\ 2} + v_{az}^{\ 2}}}{\sqrt{\overline{K}K_{ra}\phi S_a}} \\ \overline{K} = \sqrt{\left(\dfrac{1}{K_x}\dfrac{V_{ax}^{\ 2}}{V_{ax}^{\ 2}+V_{az}^{\ 2}} + \dfrac{1}{K_z}\dfrac{V_{az}^{\ 2}}{V_{ax}^{\ 2}+V_{az}^{\ 2}}\right)} \end{cases} \tag{4}$$

Equation: $\overline{K}$ —average permeability, μm^2.

(2) Considering the elastic characteristics of the highly viscous fluid, characterization based on the relationship between variable cross-section pore throat model, the relationship between the effective viscosity and the apparent viscosity of the polymer solution as follows [11].

$$\begin{cases} \mu_{eff} = (1+w)\mu_v \\ w = \dfrac{\dfrac{12n}{3n+1}(1-\dfrac{1}{\lambda_1^{\ 6}})\alpha\gamma\theta_f - \left(1-\dfrac{1}{\lambda_3}\right)\dfrac{(B^4-1)^{1/2}}{(1+\beta)(-\alpha)}}{2\left(1-\dfrac{1}{\lambda_3}\right)\dfrac{1}{\alpha}+6\xi} \end{cases} \tag{5}$$

Equation: μ_{eff}—effective viscosity of polymer solution, mPa·s; Δp_{exit}—pressure loss of extrusion pore throat polymer, MPa; β—undetermined coefficient, the polymer solution is generally 1-2; B—die swell ratio; α—inlet convergence coefficient;λ_1、λ_2、λ_3—the ratio of pore throat of Inlet convergence section, throat passage section, extrusion throat section;θ_f—time of polymer solution characteristic, s; ξ—pore factor, ratio of throat length to diameter.

2.2.2.2 residual resistance coefficient of polymer solution

The polymer solution causes a decrease in reservoir permeability during the porous flow process, mainly related to the adsorption of polymer and rock surface and the retention in porous media. The difference is that the conventional digital-analog software only considers the influence of polymer concentration on the residual resistance coefficient, without describing the polymer retention characteristics under the condition of high residual resistance coefficient [13]. Therefore, building the relationship between the residual resistance coefficient and the polymer concentration and flow rate by

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the method of bivariate polynomial nonlinear regression method.

$$\begin{cases} R_k = 1 + (RRF - 1)\dfrac{C_{ads}}{C_{ads,\max}} \\ RRF = q_1 + q_2 v_a + q_3 v_a^2 + q_4 C_p \\ C_{ads} = \min(C_{ads,mav}, \dfrac{C_p}{brk_1 + brk_2 C_p}) \end{cases} \tag{6}$$

Equation: R_k—permeability reduction factor; RRF—residual resistance coefficient; q_1、q_2、q_3、brk_1、brk_2—input parameters; C_{ads}—polymer adsorption, μg/g; $C_{ads,max}$—maximum adsorption of polymer, μg/g.

2.2.3 Definite condition

In order to ensure the uniqueness of the solution, in the reservoir numerical simulation, the corresponding boundary conditions and initial conditions must be given for the specific problem.

2.2.3.1 Initial conditions

The initial conditions, is the distribution of parameters in the initial time model, mainly include pressure, saturation and polymer concentration

$$\begin{cases} P_o = P_a = P_{wf} \\ S_a = S_{ar} \\ C_{pa} = 0 \end{cases} \tag{7}$$

Equation: P_{wf}—flowing bottom hole pressure, MPa; S_{ar}—irreducible water saturation.

2.2.3.2 Boundary Conditions

If the reservoir is viewed as a system, the inner boundary is formed at the point where the Shaft meets the reservoir. Producers adopted the production method of constant flow (Q) and production end pressure (P_{wf}) at the injection end when describing the working state of the injection well and production well inside the reservoir.

2.2.4 Numerical solution

The model calculation with implicit pressure-explicit saturation solution. The iteration is repeated several times, once iterate, the pressure, saturation and concentration equations are updated which to approach the value of the n+1th time gradually.he solution process is shown in Figure 1:

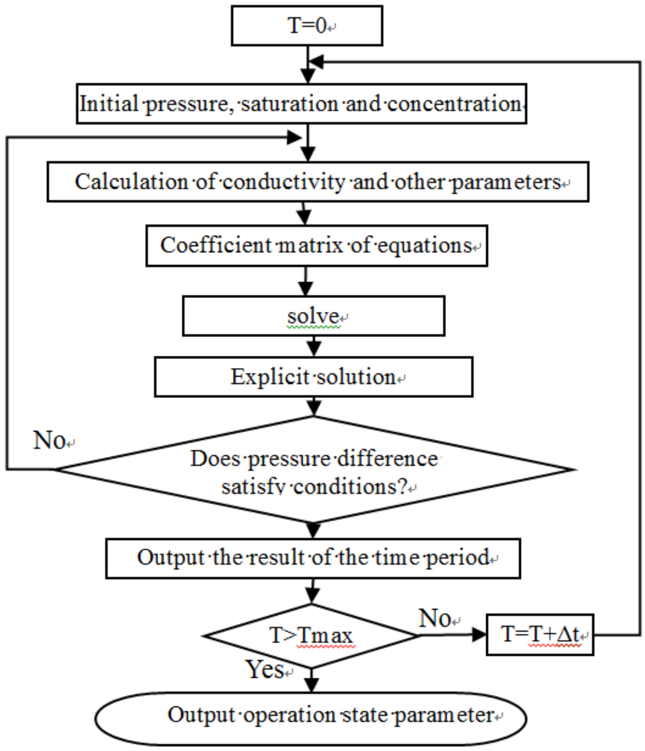

Figure 1. Polymer flooding numerical solution process

2.3 Mathematical model parameters input

As the viscosity and residual resistance coefficient of the polymer solution increase during the calculation, the injection pressure increases. At the same time it is affected by the turbulence between the layers (the difference in permeability), which is more likely to cause oscillation or divergence of the numerical solution. However, through mesh refinement and steps for convergence, this phenomenon can be improved to some extent, but it also reduces the timeliness [14]. Considering the Bohai heavy oil reservoir as a prototype, a small scale conceptual model is extracted based on the similarity theory [15].

(1) Geometric model parameters

The number of layered heterogeneous geometric models is 3∗30, and the main grid attribute parameters are shown in table 1. The injection wells and production wells are arranged along the X-direction grids.

Table 1. Grid attribute parameter table

	X dimension direction, cm	Y dimension direction, cm	Porosity	X-direction permeability, $10^{-3}\mu m^2$	Y-direction permeability, $10^{-3}\mu m^2$
Level one	30	1	0.32	2500	150
Level two	30	1	0.3	1500	150
Level three	30	1	0.28	750	150

(2) Fluid parameter

The oil, water and polymer characterization parameters are shown in table 2.

Table 2. Fluid Performance Parameter Table

Parameter	Value	Unit	Parameter	Value	Unit	Parameter	Value	Unit
a	22.52	-	D_2	2	μm	q_3	-0.1245	-
b	-0.0578	-	D_3	8	μm	q_4	2.2×10^{-3}	-
c	4.5×10^{-5}	-	β	1.4	-	brk_1	2.4313	-
d	0.5334	-	ξ	0.6	-	brk_2	8×10^{-4}	-
e	3×10^{-5}	-	B	1.2	-	P_{wf}	0.1	MPa
f	-6×10^{-8}	-	C	12	-	S_{ar}	0.1679	-
θ_f	0.1	s	q_1	-1.0805	-	μ_a	1	mPa·s
D_1	8	μm	q_2	0.7202	-	μ_o	123	mPa·s

3. Analysis of numerical simulation results

Enlarge/reduce different ratios based on the original apparent viscosity and residual resistance coefficient（the apparent viscosity is magnified by m times as α=m, the reduced m is recorded as α=1-1/m; similarly the residual resistance coefficient is enlarged by n times as β=n, and the reduced n is recorded as β=1-1/n）the polymer solution viscosity and residual resistance coefficient have influence on recovery factor and injection pressure.

3.1 Influence of residual resistance coefficient on oil displacement effect

Analyzing the change of different moisture content, recovery percent, and injection pressure of residual resistance coefficients (β=1/3, β=1, β=3, β=5) under the same viscosity (α=1). The results are shown in figure 2.

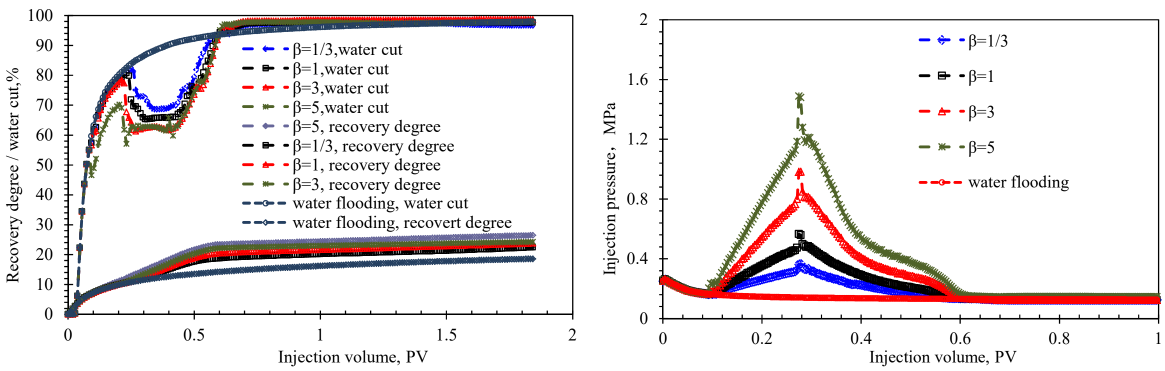

Figure 2. Recovery / water content (left) and injection pressure (right) when α=1

It can be seen from figure 2 that the increase of residual resistance coefficient makes the polymer flooding injection pressure and crude oil recovery degree increase：The increase of polymer adsorption and retention reduces the permeability of porous media, increases the injection pressure, and improves the sweep efficiency. The water-reducing funnel changes from “V” to “U”, which prolongs the low water-bearing harvest period and thus improves oil recovery factor.

3.2 Analysis of contribution of viscosity and residual resistance coefficient to polymer flooding effect

The polymer flooding effect and the injectability were measured by the degree of recovery (about 0.6 PV) and the maximum injection pressure as the reference indicators after the water content of the polymer flooding was stabilized. The data are shown in table 3.

Table 3. Combination of different viscosity and residual resistance coefficient

simulated serial number	apparent viscosity α	residual resistance coefficient *β*	recovery percent, %	injection pressure, MPa
1	1	1/3	18.79	0.32
2	1	1	20.47	0.57
3	1	3	22.12	0.98
4	1	6	23.38	1.49
5	1/3	1/3	17.03	0.23
6	1/3	1	19.03	0.36
7	1/3	3	21.18	0.56
8	1/3	6	22.79	0.8
9	3	1/3	20.94	0.52
10	3	1	21.96	0.99
11	3	3	23.12	1.91
12	3	6	24.13	2.98

(1) A three-dimensional cubic interpolation method is used to establish a corresponding phenetic relationships diagram with the help of MATLAB platform, as shown in figure 3.

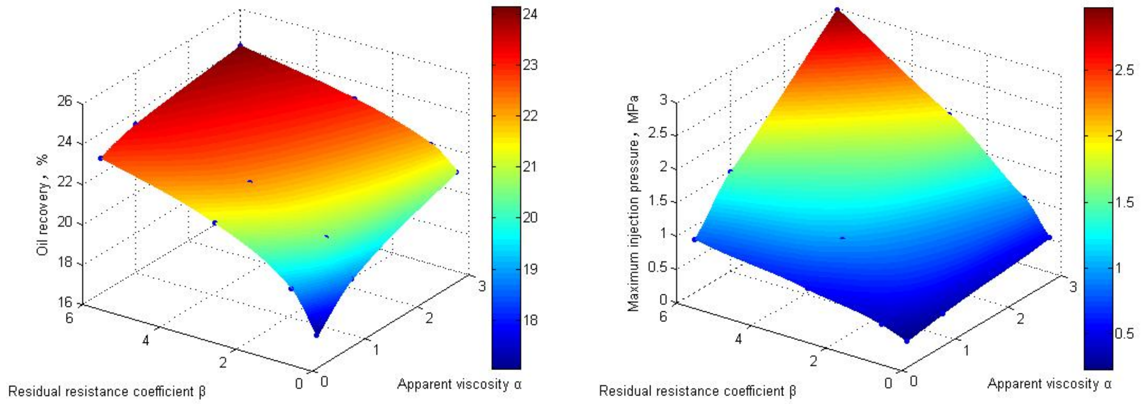

Figure 3. Combination of different viscosity and residual resistance coefficient

We can conclude from figure 3 that: ①With the increase of viscosity and increase of residual resistance coefficient, oil recovery will gradually increase (Figure A), but at the same time it will lead to reduced injection (B); ②The same values of α and β, the red area of the A map is approximately distributed between the two while the B map is more biased towards the apparent viscosity α side, indicating that the solution viscosity is the main controlling factor affecting the polymer flooding injection.

(2) The gray correlation method [16] is used to quantitatively calculate the contribution of apparent viscosity and residual resistance coefficient to polymer flooding effect, polymer solution viscosity, residual resistance coefficient and recovery percent (the water content after polymer flooding tends to Smooth) and maximum injection pressure correlation analysis are shown in table 4.

Table 4. Correlation analysis of viscosity and residual resistance coefficient on polymer flooding

	correlation, 1×10^{-3}		Contribution, %	
	Calibration recovery percent	Maximum injection pressure	Calibration recovery percent	Maximum injection pressure
apparent viscosity	76.9	85.5	48	75
residual resistance coefficient	84.7	28.9	52	25

It can be seen from table 4: ①For the layered heterogeneous heavy oil reservoir, the contribution of the viscosity of the polymer solution to the injection pressure is significantly higher than the residual resistance coefficient, and the difference between the two has little effect on the recovery factor (apparent viscosity accounts for 48%, The residual resistance coefficient accounts for 52%); ② Further analysis shows that under the same injection pressure conditions (simulation numbers 3 and 10 in table 1-3, injection pressures of 0.98 and 0.99), increasing the residual resistance coefficient of the polymer solution is more conducive to the improvement of crude oil recovery, that is, low viscosity and high residual resistance coefficient flooding system is more conducive to the mobility control ability of polymer flooding in heavy oil reservoirs.

4. Conclusion

(1) By characterizing the description of equations of the viscosity and residual resistance coefficient of polymer solution, the single factor analysis of the characteristics of polymer flooding effect from two aspects is an effective means to study the contribution of polymer mobility control.

(2) The contribution of the viscosity of the polymer solution to the injection pressure (75%) is significantly higher than the residual resistance coefficient (25%) while the contribution to the recovery factor is not obvious, and the viscosity contribution is 48% slightly lower than the residual 52% of the drag coefficient (RRF).

(3) Under the same injection pressure conditions, the low viscosity and high residual resistance coefficient is more conducive to the mobility control ability of polymer flooding in heavy oil reservoirs.

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