Blocking effect and numerical study of polymer particles dispersion flooding in heterogeneous reservoir

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Abstract. Polymer flooding has become an effective way to improve the sweep efficiency in many oil fields. Many scholars have carried out a lot of researches on the mechanism of polymer flooding. In this paper, the effect of polymer on seepage is analyzed. The blocking effect of polymer particles was studied experimentally, and the residual resistance coefficient (RRF) were used to represent the blocking effect. We also build a mathematical model for heterogeneous concentration distribution of polymer particles. Furthermore, the effects of polymer particles on reservoir permeability, fluid viscosity and relative permeability are considered, and a two-phase flow model of oil and polymer particles is established. In addition, the model was tested in the heterogeneous stratum model, and three influencing factors, such as particle concentration, injection volume and PPD (short for polymer particle dispersion) injection time, were analyzed. Simulation results show that PPD can effectively improve sweep efficiency and especially improve oil recovery of low permeability layer. Oil recovery increases with the increase of particle concentration, but oil recovery increase rate gradually decreases with that. The greater the injected amount of PPD, the greater oil recovery and the smaller oil recovery increase rate. And there is an optimal timing to inject PPD for specific reservoir.

1. Introduction
Reservoir heterogeneity has been recognized as a principle factor responsible for the low sweep efficiency of injected water or gas. Polymer flooding, foam flooding and alkaline surfactant polymer (ASP) have been applied to control conformance in water or gas flooding [1-3]. Polymer flooding could decrease the water-oil mobility ratio and diverts injected water to the un-swept zones, which has been an effective enhanced oil recovery method after water flooding [4].

As a conformance control method, polymer flooding is applied widely to improve the sweep efficiency in many oil fields, especially in China [5]. They can be transported as suspensions in water and plug some pore throats to force injected water to bypass from high permeability zones [6]. Polymeric microspheres, the important ingredient in the suspension and composed of polymer monomers, cross linkers, initiators and active agents, are very suitable for flooding of micron throat diameter reservoir. The polymer microspheres produced plugging at the throat after the injection of water into the oil layer. The blocking produces resistance for following water flow and flow around happens. When the pressure difference increases, the elastic microspheres are deformed and the polymer microspheres continue to migrate to the deep through the throat. This is the flooding
mechanism of the polymer microspheres [7]. Field application of polymer microspheres was first reported in the late 1990s. In 1996, BP oil company made a deep transfer grain-driven technology, the establishment of a "particle-controlled flooding" concept. In 1997, BP, Mobil, Chevron Texaco and Ondeo Nalco jointly developed a time-delayed and highly expansive material for deep profile control and named the technology "Bright Water" [8, 9]. Since then, many institutions have conducted pilot studies, and indicated that the technology is applicable to deep profile flooding, which has a good regulation of the permeability. Polymer microspheres flooding has been proven as an effective method to increase oil and decrease water, and has achieved good economic benefits [10-12].

Some experimental studies on the behavior and characteristics of gel particles transport through porous media. Three types of flow patterns were proposed, including passing, breaking and passing, and plugging [13]. An experimental and theoretical study on the mechanisms of conformance control by the propagation of gel particles and their deposition into a porous medium for post-polymer flooding reservoirs was conducted by Feng, Chen and Zhang [14]. Their 3D model could simulate the conformance control process and optimize the injection parameters of the gel particles.

The sweep efficiency of the polymer solution in the layered heterogeneous model has been calculated by many researchers. A kinetic model for polymer degradation is proposed which is used to obtain the radial viscosity profile of the degrading polymer. This may in turn be used to calculate the steady-state pressure drops associated with the degrading polymer [15]. Experiments and numerical simulations were used to study fundamental changes in viscous fingering due to the crosslinked-polymer reaction. When the crosslinking reaction is fast enough so that it occurs during injection, the viscous instability becomes somewhat damped, resulting in less distinct fingers and a nearly plug-flow displacement in some cases. The differences are because gelation causes a large pressure gradient to form just behind the displacement front, whereas non-reactive fingering is caused by a small pressure gradient within the fingering zone [16]. The mechanism of polymer solution microscopically increasing oil recovery is due to the viscoelastic characteristic of the polymer solution, the sweeping force acting on the residual oil by the viscoelastic polymer solution is larger than that of water. The residual oil is not pushed out by the polymer solution but pulled out by the polymer solution [17]. The viscoelastic flooding fluid displaces the residual oil with two forces, one is the force to overcome the capillary force perpendicular to the oil-water interface, and the other is the traction force that drives the residual oil parallel to the oil-water interface [18].

Although the study on the mechanism of polymer flooding has been quite mature, the influence of polymer particles on the seepage during oil displacement is still need to be further studied. Many scholars have analyzed the viscosity and the injection rate of the polymer. However, the relationship between the pore and the polymer particle size, and polymer particle concentration are not clear, which deserves further study. In this paper, the effects of polymer particles on reservoir permeability, fluid viscosity and relative permeability are considered, and a two-phase flow model of oil and polymer particles is established. In addition, the model was tested in the heterogeneous stratum case, and three influencing factors, such as particle concentration, injection volume and PPD (short for polymer particle dispersion) injection time, were analyzed.

2. Experiment

2.1. Polymer particles blocking tests
Blocking tests are carried out using core flooding devices. Water flooding starts after the core is saturated with formation water. When the pressure stabilizes for a while, the PPD starts to be injected. Follow-up water flooding is conducted when the pressure is stable again. The pressure changes during the experiment are recorded. Displacement experiment flow chart is expressed in Figure 1.

2.2. Experiment analysis
In the whole flooding process, the measure of water permeability decreased, which is caused by retention or partial clogging of the polymer particles in porous media, is represented by RRF. This
coefficient is defined and calculated as equation (1). In the equation, \( \Delta P_1 \) is the stable differential pressure of the inlet and outlet at the period of initial water flooding, \( \Delta P_2 \) is the stable differential pressure at the period of follow-up water flooding. Unit of above differential pressure is MPa.

\[
\text{RRF} = \frac{\Delta P_2}{\Delta P_1}
\]  

(1)

RRF of PPD system through core also has relationship with permeability of the porous medium, particle size, particle concentration and injection rate. Permeability and particle size are unified as one parameter, which is particle size to the average pore throat radius of the core ratio. The experimental injection flow rate was converted into the seepage velocity as equation (2) In equation (2), \( v \) is the seepage velocity with unit m/d. \( Q \) is the injection flow rate with unit cm\(^3\)/min. \( A \) is the cross sectional area of core with unit cm\(^2\).

\[
v = \frac{14.4Q}{A}
\]  

(2)

Getting from experimental data relationships of above parameters are expressed in Figure 2, 3 and 4.

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**Figure 1.** Displacement experiment flow.

**Figure 2.** Curve of RRF and particle size and average pore throat radius ratio.

**Figure 3.** Curve of RRF and injection rate.
Based on the above single factor analysis, we propose an empirical equation, which is expressed as equation (3). In equation (3) a, b, c and d are model parameters. Con is the polymer particle concentration with unit g/L. Dr is the particle size and average pore throat radius ratio with dimensionless unit. V is the injection rate with unit m/d. All the experimental data were fitted by multivariate nonlinear fitting method and parameters can be calculated, which are $a = 16.16$, $b = 0.62$, $c = 0.42$ and $d = 1.26$.

$$RRF = a(\text{Con})^b(\text{Dr})^c(V)^d$$ (3)

3. Heterogeneous flow

3.1. Flow phenomenon

After the hydration of the polymer particles, the internal structure is filled with water. Particles are easily deformed by shear stress and move to throat centre. So the distribution of particle concentration in porous media is heterogeneous.

Figure 5 shows that the fluid flows in from the upper side and flows out from the lower two outlets. Sub-figure a shows the concentration of particle, dominated by Brown force and whose diameter is less than 1 µm, is evenly distributed in the two outlets. Sub-figure b shows the concentration of particle at low-velocity exit microtubule, dominated by shear force and whose diameter is larger than 1 µm, is far less than the injection concentration.

$$f_i = \frac{q_i}{\sum_{i=1}^{N} q_i}, \text{ for } i = 1...N$$ (4)
Volume concentration component of each outlet microtubule is defined and listed in equation (5), in which $\phi_{avg}$ is polymer particle volume concentration at node P and $\phi_i$ is polymer particle volume concentration at the ith outlet.

$$\theta_i = \frac{\phi_i}{\phi_{avg}}$$  \hspace{1cm} (5)

Mass conservation of fluid and particles can be expressed as equation (6) and equation (7).

$$\sum_{i=1}^{N} f_i = 1$$  \hspace{1cm} (6)

$$\sum_{i=1}^{N} f_i \theta_i = 1$$  \hspace{1cm} (7)

Referring the expression of red cell dendritic fraction concentration, polymer particle volume concentration component of any N outlets can be expressed as equation (8).

$$\theta_i(f_i) = a + \frac{1-a}{Nf_i}, i = 1...N$$  \hspace{1cm} (8)

When $\theta_i = 0$, $f_i$ is defined as critical flow rate $f_i^*$. If $f_i$ is less than $f_i^*$, $\theta_i$ still equals to 0. So equation (8) is modified to piecewise function form, listed in equation (9), in which $f_i$ is the sum of all the outlet flows which meet the criteria $f_i > f_i^*$ and $N$ is the number.

$$\begin{cases} 
\theta_i(f_i) = a + \frac{1-a}{Nf_i}, f_i > f_i^* \\
\theta_i(f_i) = 0, f_i \leq f_i^*
\end{cases}$$  \hspace{1cm} (9)

In above equations parameter $a$ is defined as particle phase separation degree. It has relationship with particle size and shear modulus. The smaller shear modulus or the bigger particle size, the bigger $a$, that is the more obvious the particle phase separation phenomenon. $a=1$ means the particle concentration is homogeneous.

4. Longitudinal heterogeneous formation displacement model

4.1. Characteristic equation

Referring Krige-Dougherty viscosity concentration equation [19], the viscosity of PPD can be expressed as equation (10), in which $Con$ is the concentration of PPD, $\mu_w$ is water viscosity, $\phi_m$ is the max volume concentration of PPD, $\lambda$ is the volume of a unit mass after expansion of polymer particles and $\eta^*$ is the characteristic viscosity.

$$\mu_d = \mu_w (1 - \frac{\lambda Con}{\phi_m})^{-\eta^*}$$  \hspace{1cm} (10)

The concentration of polymer particles in different layers can be calculated with equation (10). Particle phase mass concentration of dispersed slugs is weighted average of daily injections, expressed in equation (11), in which $q_j$ is the day $j$ injection and $Con_j$ is the day $j$ particle phase concentration.

$$Con = \frac{\sum_j q_j Con_j}{\sum_j q_j}$$  \hspace{1cm} (11)

RRF can be calculated with equation (3), in which parameters can be obtained by experimental data. Modified absolute permeability is expressed as equation (12), in which $k$ is the original absolute
permeability. Modified residual oil saturation can be calculated with equation (13), in which $S^\text{or}_\text{er}$ is the original residual oil saturation, $c_1$, $c_2$ and $c_3$ are function indexes, $P_V$ is the volume fraction of the injected dispersion.

$$k_p = \frac{k}{RRF}$$

$$S^\text{or}_\text{er} = S^\text{or}_\text{er} - \frac{c_1 \text{Con}[1 - e^{-c_2 P_V}]}{1 + c_3 \text{Con}}$$

4.2. Stratified flow equation

After injecting PPD into stratified heterogeneous strata, slug flow is formed in each layer. The purpose of this model becomes to solve the problem of multi-stage multi-plug pressure solution. Flooding schematic is showed in Figure 6.

![Flooding schematic](image)

Figure 6. Flooding schematic.

As we know the relationship between pressure and flow rate of any slug in one dimension polar coordinates can be expressed as equation (14), in which $r$ is the distance from centre well, $p$ is the pressure of distance $r$, $h$ is the layer height, $k$ is the absolute permeability, $k_r$ is the relative permeability, $\mu$ is viscosity, subscript $w$ and $o$ represent water and oil, subscript 0 and f represent both ends of the slug.

$$p_r - p_0 = \frac{1}{k_w + k_o} \frac{1}{2k_r \pi h} \ln \left( \frac{r_f}{r_0} \right) q$$

If there are two slugs, particle dispersion/oil and water/oil, in one layer, the pressure difference across the layer is listed in equation (15), in which $R_i$ is seepage resistance, $i$ is the layer number.

$$\Delta p = \left[ \frac{1}{\mu_p} + \frac{1}{\mu_w} \frac{2k_r \pi h_i}{2k_i \pi h_i} \ln \left( \frac{r_f}{r_0} \right) + \frac{1}{\mu_o} + \frac{1}{\mu_w} \frac{2k_r \pi h_i}{2k_i \pi h_i} \ln \left( \frac{r_f}{r_0} \right) \right] q_i = R_i q_i$$

The pressure at both ends of each layer is equal. So equation (16) is listed, in which $N$ is stratification number of heterogeneous reservoir.

$$\Delta p = R_i q_i = \ldots = R_N q_N$$

If the total injection flow rate is constant as $q_{\text{inj}}$. The relationship between pressure and injection volume is expressed as equation (17). So any layer flow can be expressed as equation (18). Following Slug length and water saturation can be calculated at any time.
\[
\Delta p = \frac{q_{\text{inj}}}{R_1} + \frac{1}{R_2} \cdots + \frac{1}{R_N} \quad \text{(17)}
\]

\[
R_i = \frac{1}{\frac{q_{\text{inj}}}{R_i} + \frac{1}{R_1} + \cdots + \frac{1}{R_N}} \quad \text{(18)}
\]

5. Example calculation and results

The simulation process is divided into three stages, initial water flooding, PPD flooding, following water flooding. When water content of whole model gets 80%, PPD starts to be injected. If PPD injection volume gets specified amount, following water flooding starts to be injected. If water content of whole model gets 98%, simulation stops. The model is solved iteratively and time step is one day. At the period of PPD flooding, modified residual oil saturation, polymer particle concentration, and absolute permeability can be calculated with above equations.

There are two layers in this simulation, including higher permeability 100 mD layer and lower permeability 20 mD layer. Height of each layer is 3 m and porosity is 0.3. Oil viscosity is 5 mPa·s. Water viscosity is 1 mPa·s. Well distance is 150 m. Injection well daily rate is 50 m³/d and production well bottom hole pressure is 3 MPa. Irreducible water saturation and residual oil saturation of water-oil flow are 0.3 and 0.35. The volume of a unit mass is from expansion experimental data fitting. \( c_1, c_2 \) and \( c_3 \) of equation (13) are 3.5*10^{-4}, 2.35, 2.9*10^{-3}. The value of particle phase separation degree \( a \) can get from equation (19), in which \( d_p \) is particle diameter.

\[
\left\{
\begin{array}{l}
\quad a = 1, \quad d_p \leq 1 \mu m \\
\quad a = 1.5, \quad 1 \mu m < d_p < 2 \mu m \\
\quad a = 2, \quad d_p \geq 1 \mu m
\end{array}
\right. \quad \text{(19)}
\]

5.1. Contrast of PPD flooding and water flooding

In this simulation the concentration of injection PPD is 2 g/L. Amount of slug equals 0.1 times pore volume. The diameter of particle is 2 µm. Figure 7 shows that after changing water to polymer, oil recovery increases and after changing PPD flooding to following water flooding, the growth rate of oil recovery gradually slows down. It demonstrates that PPD can effectively improve the recovery of heterogeneous reservoir, and heterogeneous concentration distribution dispersion is better than homogeneous.

Figure 7. Curves of injection volume and oil recovery with different flooding method.

Figure 8. Curves of injection volume and oil recovery with different flooding method and permeability.
Figure 8 shows the relationship of injection volume of PPD and stratified oil recovery. It is concluded that oil recovery of heterogeneous dispersion flooding in low permeability is bigger than homogeneous dispersion flooding about 0.03. But two values in high permeability are similar. Result shows that heterogeneous dispersion flooding can improve sweep efficiency and increase flow in low permeability.

5.2. Particle concentration
After moisture content of production liquid in water flooding gets 0.8 and other parameters are kept constant, different polymer particle concentration dispersions are injected. Figure 9 shows that oil recovery increases with the increase of particle concentration. But Figure 10 shows that oil recovery increase rate gradually decreases with the increase of particle concentration.

![Figure 9. Curves of injection volume and oil recovery with different dispersion concentration.](image1)

![Figure 10. Curves of injection volume and dispersion concentration.](image2)

5.3. Injection volume
After moisture content of production liquid in water flooding gets 0.8 and other parameters are kept constant, PPD with different volumes are injected. Figure 11 shows that with the continuous injection of polymer particles oil recovery increases rapidly, but increase rate of following water flooding slows down. The more injection volume of PPD, the higher oil recovery. It can be concluded that increasing injection volume of PPD can improve the blocking effect to high permeability. In addition, the larger the amount of dispersion into system, the retention of particles more and the greater decline in absolute permeability. The injection of PPD can decrease permeability ratio of heterogeneous Reservoir. Figure 12 shows that the greater the injection amount of PPD, the greater oil recovery. But according to the curve slope in Figure 12, when the injection amount exceeds 0.1 PV, the increase extent of oil recovery decreases rapidly.

5.4. PPD injection time
In case that other parameters are kept constant, after moisture content of production liquid in water flooding gets different values, PPD are injected. Figure 13 shows that the earlier the PPD is injected, the higher the oil recovery of low permeability layer. When the water content is 90%, oil recovery of the low permeability layer after injecting PPD is about 12% lower than the water content of 30%. On the contrary, the later the PPD is injected, the higher the oil recovery of high permeability layer. It can be concluded that in order to improve sweep efficiency and improve oil recovery of low permeability layer, PPD can be injected when water content is relatively low. Considering the recovery of high permeability layer and low permeability layer in this simulation, it is the better timing to inject PPD when water content gets 0.7.
6. Conclusion
In this paper, the blocking effect of polymer particles was studied experimentally. Based on the experimental data and multivariate nonlinear fitting method, we propose an empirical equation to clarify the relationship of RRF and polymer particle concentration, injection rate, radius ratio of particle and average pore throat. We also build a mathematical model for heterogeneous concentration distribution of polymer particles. At last, a numerical model of PPD flooding in heterogeneous reservoir is established. The semi-analytical method is used to describe PPD flow motion and influencing factors are analyzed.

Simulation results show that PPD can effectively improve sweep efficiency and especially improve oil recovery of low permeability layer. Oil recovery increases with the increase of particle concentration, but oil recovery increase rate gradually decreases with that. The greater the injection amount of PPD, the greater oil recovery and the smaller oil recovery increase rate. And there is an optimal timing to inject PPD for specific reservoir.

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