Mathematical model of nano /micron-sized polymeric particles flooding

Y Q Long¹, X H Huang², F Q Song², R Y Wang² and L Q Chen¹

¹Institute of Innovation & Application, Zhejiang Ocean University, Zhoushan, 316022, China
²School of Petrochemical & Energy Engineering, Zhejiang Ocean University, Zhoushan, 316022, China
E-mail: longyunqian@163.com

Abstract. In order to achieve the diversion of fluid flow, exploit the remaining oil in small pores and improve the oil recovery, a method of nano/micron-sized polymeric particles flooding was applied to low permeability reservoirs. The inhomogeneous flooding experiments show that the nano/micron-sized polymeric particles can greatly expand the wave volume and reduce the water content with an increase of 7.4%, 16.5% and 26.8% in the high, medium and low permeability layers, respectively. Based on the analysis of its percolation mechanism and percolation law, the mathematical model of nano/micron-sized polymeric particles flooding was established according to the mass transfer fluid mechanics, the chemical dynamics and the principle of material balance. The numerical simulation results show that it is feasible to carry out the nano/micron-sized polymeric particles flooding in low permeable and high water cut oilfields. It can increase the oil recovery of 7.6% and achieve better oil displacement effect.

1. Introduction

The nano/micron-sized polymeric particles flooding is a new method of tertiary oil recovery developed on the basis of particle plugging agent and polymer flooding technology[1,2]. The functional polymeric particles were prepared using materials science and technology, which could swell in water[3]. In the process of oil displacement, nano/micron-sized polymeric particles have the function of choosing to flow into strata, enlarging the swept volume and enhancing oil washing efficiency, resulting in achieving the diversion of fluid flow, effectively blocking the high permeability layer, controlling water channeling and increasing oil displacement efficiency[4]. A large number of experiments results showed that the nano/micron-sized polymeric particles had the characteristics of blocking a big pore, so that they can flow or stagnant in the form of net distribution in the macropores to achieve the effect of profile control step by step[5]. Compared with water flooding, the relative permeability of the two phases produced favorable changes for oil displacement[6]. The indoor experimental oil recovery was more than 5% higher than that of water flooding[7].

The current model equations were difficult to reasonably describe the complex seepage during the nano/micron-sized polymeric particles flooding because of the factors such as the percolation characteristics, the swelling, the seepage resistance, the blockage and the particles breakage. Based on the study of the percolation mechanism and the seepage law of nano/micron-sized polymeric particles flooding, the mathematical models were systematically established to overcome the shortcomings of
the existing mathematical models according to the principle of transport hydrodynamics, chemical dynamics and material balance in this study.

2. Oil displacement experiments in parallel cores

Oil and formation brine samples were collected from Daqing oil field. The oil was centrifuged at 5,000 rpm at 30°C for 2 h to remove water and solids from the oil. The oil had a viscosity of 11.2mPa·s and density of 0.856 g/cm³ at 50°C. The formation brine had a salinity of 5.4wt%. The nano/micron-sized polymer spheres were dispersed in a 1.5wt% aqueous solution with viscosity of 1.38mPa·s. After the cores were saturated with formation brine and weighed, the cores were flooded with the crude oil. The oil injection was continued until water production ceased. The cores were flooded by water first. The injection of the formation brine was continued until the oil production became negligible. Then, a nano/micron-sized polymeric particles slug of 0.5 PV (pore volumes) was injected, followed by an extended waterflood until the oil production stopped.

The test results are shown in Table 1 and Figure 1. Table 1 shows that after injecting nano/micron-sized polymeric particles slug, the oil recovery was enhanced by 26.8%, 16.5% and 7.4% respectively in the low, middle and high permeability cores. Figure 1(a) shows that the oil recovery enhanced in high permeability core was more than that in the middle and low permeability cores during the waterflood injection, while the oil recovery increased greatly in the middle and low permeability cores after injecting nano/micron-sized polymeric particles. Figure 1(b) shows that the water cut in the high permeability core was less than that in the middle and low permeability cores during the waterflood injection, while the water cut decreased greatly in the middle and low permeability cores after injecting nano/micron-sized polymeric particles. The lowest water cut were 72.8%, 68.7% and 60.7% in the high, middle and low permeability cores, respectively. The above results illustrate that it is effective in enhancing the oil recovery and decreasing the water cut in the reservoirs for nano/micron-sized polymeric particles flooding.

![Figure 1. Production performance for nano/micron-sized polymeric particles flooding.](image)

**Table 1** Oil Displacement efficiency of nano/micron-sized polymeric particles flooding

| Parallel model | Gas permeability ($\times 10^{-3}$, $\mu$m²) | Initial oil saturation(%) | Waterflood recovery(%) | Final oil recovery(%) | Enhanced oil recovery(%) |
|----------------|-------------------------------------------|---------------------------|------------------------|----------------------|-------------------------|
| Low            | 12                                        | 63.1                      | 24.6                   | 51.4                 | 26.8                    |
| Middle         | 53                                        | 66.8                      | 42.3                   | 58.8                 | 16.5                    |
| High           | 97                                        | 68.7                      | 55.1                   | 62.5                 | 7.4                     |
3. Flow mathematical model for nano/micron-sized polymeric particles flooding

3.1. Flow mathematical model
The basic hypotheses were as follows: (1) Underground fluids were divided into three phase, namely water phase, oil phase and nano-micron polymer aqueous solution phase. (2) Fluids were composed of six components, namely water, oil, nano-micron polymer, divalent cation, total anion and stabilizer. (3) Water and oil were respectively distributed in water phase and oil phase. (4) Nano-micron polymer was only distributed in water phase. Other ions were regarded as tracers whose volumes could be neglected. (5) All rocks and fluids could be compressed. (6) The rocks had characteristics of anisotropy and heterogeneity. (7) The influences of convection diffusion, capillary force and gravity were considered. Based on a series of experiment research results on the porous flow mechanism, flow mathematical models were established. The mass conservation equation can be expressed as follows:

\[
\frac{\partial}{\partial t} \left[ \phi \sum_{j=1}^{Nc} \rho_j S_j C_i + (1 - \phi) \rho_s C_{is} \right] + \nabla \cdot \left[ \sum_{j=1}^{Nc} \rho_j \vec{u}_j C_j + \sum_{j=1}^{Nc} \rho_j \phi S_j \left[ \sum_{k=1}^{Nc} D_{ikj} \text{grad} C_i \right] \right] = 0
\]

(1)

Where \( i=1,2,3 \ldots, Nc; \ j=1,2,3 \ldots, Np; \) \( Nc \) is the number of components; \( Np \) is the number of phases; \( t \) is the time; \( \phi \) is the porosity; \( C_i \) is the fluid phase mass fraction; \( C_{is} \) is the solid phase mass fraction; \( S_j \) is the j phase saturation; \( ps \) is the solid phase density; \( p_j \) is the j phase density; \( C_{ij} \) is the mass fraction of i component in j phase; \( D_{ikj} \) is the diffusion coefficient between i and k components in j phase; \( \vec{r}_{ij} \) is the the amount of generation and coalescence of i component in j phase; \( \vec{r}_{is} \) is the amount of solid phase trapping i component.

Because the flow is nonlinear, the motion equation of each phase is expressed as follows:

\[
\vec{u}_j = -K \frac{k_0}{\mu_j R_j} (\nabla P_j - \rho_j g \nabla Z)
\]

(2)

Where \( K \) is the absolute permeability; \( k_{rj} \) is the relative permeability of j phase; \( \mu_j \) is the j phase viscosity; \( R_j \) is the j phase coefficient of permeability decline; \( P_j \) is the j phase pressure; \( g \) is the acceleration of gravity; \( Z \) is the reservoir depth.

3.2. Flow characteristics equation

3.2.1. Hydration expansion equation
The initial size of nano/micron-sized polymeric particles is accord with normal distribution, with ranging from 0.01 to 0.2μm. After hydrated its size is still in accordance with normal distribution, with ranging from 1 to 20μm. Its radius after hydrated is expressed as follows:

\[
r = r_0 (1.0 + \frac{a_{sh} t_w}{b_{sh} + c_{sh} t_w})
\]

(3)

Where \( r \) is the size of nano/micron-sized polymeric particles after hydrated; \( r_0 \) is the initial size of nano/micron-sized polymeric particles; \( t_w \) is the hydration time; \( a_{sh}, b_{sh} \) and \( c_{sh} \) are the equation coefficients determined by experiments.

3.2.2 Relation matching with reservoir
The throat radius is expressed as follows:

\[
r_{\text{throat}} = 0.8529 K^{0.4354}
\]

(4)
Where, \( r_{throat} \) is the throat radius. There are four migration patterns for nano/micron-sized polymeric particles in the reservoir: (1) When \( r/r_{throat} \leq 1 \), the particles go smoothly through the throat; (2) When \( 1 < r/r_{throat} \leq 2 \), the particles go through the throat by elastic deformation to overcome resistance; (3) When \( 2 < r/r_{throat} \leq 6 \), the particles are crushed to overcome resistance for going through the throat; (4) When \( r/r_{throat} > 6 \), the particles are blocked by throats resulting in decreasing permeability greatly.

### 3.2.3 Blockage pressure equation

When \( r/r_{throat} \geq 1.5 \), there is blockage pressure at the throat which is expressed as follows:

\[
P_r = 0.01X^2 + 1.10X - 1.46
\]

Where \( X = r/r_{throat} \), \( P_r \) is the blockage pressure.

### 3.2.4 Drag coefficient equation

\[
R_k = (1.0 + \frac{(R_{k,\text{max}} - 1.0)b_kC_p}{1.0 + c_kC_p})
\]

Where \( R_k \) is the reduction coefficient of permeability; \( C_P \) is the concentration of nano/micron-sized polymeric particles; \( R_{k,\text{max}} \) is the maximum reduction coefficient of permeability; \( b_k, c_k \) are the equation coefficients determined by experiments.

### 3.2.5 Residual resistance factor equation

\[
R_{rf} = (1 + \frac{a_k}{K})(1 + a_{s1}S_w + a_{s2}S_w^2)
\]

Where \( R_{rf} \) is the residual resistance coefficient; \( S_w \) is the water saturation; \( a_k, a_{s1}, a_{s2} \) are the equation coefficients determined by experiments.

### 3.2.6 Viscosity equation

\[
\mu_{nw} = \mu_w(1 + a_vC_p)
\]

Where \( \mu_{nw,\text{max}} \leq 2 \). \( \mu_w \) is the viscosity of nano/micron-sized polymeric particles solution; \( \mu_w \) is the water viscosity; \( a_v \) is the equation coefficient determined by experiments.

### 3.2.7 Relative permeability equation

\[
k_{ro} = k_{ro}^0
\]

\[
k_{rw} = k_{rw}^0(1 - S_w)^{1 + aC_p}
\]

Where \( k_{ro} \) is the relative permeability of oil phase; \( k_{ro}^0 \) is the initial relative permeability of oil phase; \( k_{rw} \) is the relative permeability of polymer particles aqueous solution; \( k_{rw}^0 \) is the initial relative permeability of water phase; \( a \) is the equation coefficient determined by experiments.

### 3.2.8 Precipitation equation

When \( r/r_{throat} \geq 2 \), the nano/micron-sized polymeric particles were crushed to precipitation. Then its concentration could be expressed as follows:

\[
C_p' = 0.1 \frac{a_dC_p}{1 + b_dC_p}
\]

Where \( C_p' \) is the concentration of micron-sized polymeric particles after breakage; \( a_d, b_d \) are the equation coefficients determined by experiments.
4. Numerical simulation analysis

A reverse rhythm profile model was established in numerical simulation calculation. The model is divided into nine layers permeabilities of which are respectively 450, 400, 350, 300, 250, 200, 150, 100 and 50mD from up to down, with a water saturation of 0.45 and porosity of 0.24. The grid of model is $9 \times 9 \times 9$, grip step $dx$, $dy$, $dz$ are respectively 15, 15, 2.0 m. The simulation results are shown in Figure 2. The results show after waterflooded for 1600 days, water cut increases to 80.39%. Then the model was flooded by nano/micron-sized polymeric particles, which could still improve oil recovery and decrease greatly water cut. The final recovery of nano/micron-sized polymeric particles flooding increases by 7.40% and the water cut of nano/micron-sized polymeric particles flooding decreases by 16.73%. These illustrate nano/micron-sized polymeric particles flooding could greatly enhance oil recovery for high water cut reservoir.

![Simulation results of nano/micron-sized polymeric particles flooding](image)

(a) Oil recovery  (b) Water cut

Figure 2. Simulation results of nano/micron-sized polymeric particles flooding.

5. Conclusions

In this study, the inhomogeneous flooding experiments were carried out. The experimental results show that the nano/micron-sized polymeric particles flooding can greatly expand the wave volume and reduce the water content with an increase of 7.4%, 16.5% and 26.8% in the high, medium and low permeability layers, respectively.

Based on a series of flow experiments, the percolation characteristic equations were set up to represent hydration swelling, percolation resistance, plugging effect, relative permeability, particle breakage and residual resistance factor of nano/micron-sized polymeric particles. The percolation mathematical models were established to describe interaction, transmission and mass conversion of water, oil and nano/micron-sized polymer particles during the nano/micron-sized polymeric particles flooding. The numerical simulation results show it is feasible to carry out the nano/micron-sized polymeric particles flooding in low permeable and high water cut oilfields. It can increase the oil recovery of 7.6% and achieve better oil displacement effect.

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