International Journal of Control and Automation
Vol.6, No.5 (2013), pp.297-314
http://dx.doi.org/10.14257/ijca.2013.6.5.26

Study and Application of Numerical Simulation of Deep Profile Control with Weak Gel

Zhou Yazhou and Yin Daiyin

Institute of Petroleum Engineering, Northeast Petroleum University, China
zhouyazhou720@163.com, yindaiyin@163.com

Abstract

With the development of numerical reservoir simulation technology, numerical simulation has been widely applied to studies on the mechanics of all chemical flooding and injection approaches. In this study, a mathematical model for three-dimensional two-phase six-component deep profile control with weak gel is established based on the mechanics of deep profile control with weak gel. The established model takes diffusion, crosslinking reaction, adsorption, degradation and other physical or chemical phenomena into consideration. A numerical simulation software for deep profile control with gel was created with FOR99 programming language. Using this software, we performed optimization on the slug combination and slug size for the intra-flooding deep profile control with gel in ASP flooding for Xingbei development zone of Daqing oil field. The analysis on the mechanics of deep profile control with gel demonstrated that the addition of the profile control system could strengthen the profile adjustment effect. After the crosslinking system is injected into oil layer, less displacing fluid could enter the high-permeability layers, stimulating more displacing fluid to enter moderate or low-permeability layers, thereby the oil displacement effect is improved.

Keywords: *weak gel, numerical simulation, deep profile control; mathematical model*

1. Introduction

Deep profile control with weak gel is a new technology integrated with the characteristics of polymer flooding. Weak gel combined the characteristics of conventional water shutoff profile control and polymer flooding, it can modify and improve the heterogeneity of the formations in deep reservoirs in order to redirect the fluid and expand the swept volume [1-3]. Meanwhile, weak gel can be used as displacing phase to improve the unfavorable mobility ratio of water flooding, thereby increasing the oil displacement efficiency of the injected water. The profile control ability of weak gel is embodied in its macromolecules, which could improve both horizontal and vertical heterogeneities of reservoirs, adjust the permeability difference between the water-adsorbing profiles and the reservoir, redirect the subsequent fluids, and expand the swept volume [4-5]. The flooding mechanism of weak gel: by increasing the water viscosity and improving the mobility ratio of water flooding, weak gel can improve the displacing efficiency and eventually increase the oil recovery rate. In this paper, we will introduce a numerical simulation method for deep profile control with weak gel. A mathematical model of deep profile control with weak gel is established, descriptions of related physical and chemical mechanisms are given, and the difference method that is stable and fast is adopted to solve related partial differential equations. With the established model, we conducted injection approach optimization for intra-flooding deep profile control

ISSN: 2005-4297 IJCA

with gel in ASP flooding. This study provides guidance for the implementation of mining methods.

2. Mathematical Model for Deep Profile Control with Weak Gel

2.1. Assumptions

1) Rocks and Fluids are compressible;

2) Seepage in the whole process is isothermal;

3) The movement of fluids follows the Darcy's law;

4) The diffusion in the process follows the Fick's law;

5) Chemical reactions only occur between polymer and crosslinker;

6) Impact of plugging agent on water-phase density can be ignored;

7) Fluid is composed by oil phase, water phase, and six pseudo-components including oil, water, polymer, crosslinker, gel, and salt; oil phase only contains oil component, and the other components are contained in water phase;

8) Balance among the phases is reached instantly;

9) The adsorption of polymer, crosslinker, and gel on rock surfaces follows the Langmuir isothermal adsorption theory, and the process is irreversible;

10) The residual resistance factor has influence on the permeability rates of both oil phase and water phase.

2.2. Establishment of the mathematical model for deep profile control with Gel

Equation (1-6) are the mathematical models for each component established according to the law of conservation of mass.

Oil:
$$\nabla\left[\frac{\rho_{\mathrm{o}}KK_{\mathrm{ro}}}{R_{\mathrm{k}}\mu_{\mathrm{o}}B_{\mathrm{o}}}\left(\nabla p_{\mathrm{o}}-\gamma_{\mathrm{o}}\nabla D\right)\right]+q_{\mathrm{o}}=\frac{\partial}{\partial t}\left(\phi\rho_{\mathrm{o}}S_{\mathrm{o}}\right) \tag{1}$$

Water:
$$\nabla\left[\frac{\rho_{\mathrm{w}}KK_{\mathrm{rw}}}{R_{\mathrm{k}}\mu_{\mathrm{w}}B_{\mathrm{w}}}\left(\nabla p_{\mathrm{w}}-\gamma_{\mathrm{w}}\nabla D\right)\right]+q_{\mathrm{w}}=\frac{\partial}{\partial t}\left(\phi\rho_{\mathrm{w}}S_{\mathrm{w}}\right) \tag{2}$$

Polymer:
$$\nabla(C_{\mathrm{p}}\frac{\rho_{\mathrm{w}}KK_{\mathrm{rw}}}{R_{\mathrm{k}}\mu_{\mathrm{w}}B_{\mathrm{w}}}\left(\nabla p_{\mathrm{w}}-\gamma_{\mathrm{w}}\nabla D\right))+\nabla\left(D_{\mathrm{p}}\phi_{\mathrm{p}}\rho_{\mathrm{w}}S_{\mathrm{w}}\nabla C_{\mathrm{p}}\right)+\phi\rho_{\mathrm{w}}S_{\mathrm{w}}R_{\mathrm{pre}}+q_{\mathrm{p}}=\frac{\partial}{\partial t}(\phi_{\mathrm{p}}\rho_{\mathrm{w}}S_{\mathrm{w}}C_{\mathrm{p}}+\rho_{\mathrm{r}}(1-\phi)C_{\mathrm{pad}}) \tag{3}$$

Crosslinker:
$$\nabla(C_{\mathrm{c}}\frac{\rho_{\mathrm{w}}KK_{\mathrm{rw}}}{R_{\mathrm{k}}\mu_{\mathrm{w}}B_{\mathrm{w}}}\left(\nabla p_{\mathrm{w}}-\gamma_{\mathrm{w}}\nabla D\right))+\nabla\left(D_{\mathrm{c}}\phi\rho_{\mathrm{w}}S_{\mathrm{w}}\nabla C_{\mathrm{c}}\right)+\phi\rho_{\mathrm{w}}S_{\mathrm{w}}R_{\mathrm{cre}}+q_{\mathrm{c}}=\frac{\partial}{\partial t}(\phi\rho_{\mathrm{w}}S_{\mathrm{w}}C_{\mathrm{c}}+\rho_{\mathrm{r}}(1-\phi)C_{\mathrm{cad}}) \tag{4}$$

Gel:
$$\nabla(C_{\mathrm{g}}\frac{\rho_{\mathrm{w}}KK_{\mathrm{rw}}}{R_{\mathrm{k}}\mu_{\mathrm{w}}B_{\mathrm{w}}}\left(\nabla p_{\mathrm{w}}-\gamma_{\mathrm{w}}\nabla D\right))+\nabla\left(D_{\mathrm{g}}\phi_{\mathrm{g}}\rho_{\mathrm{w}}S_{\mathrm{w}}\nabla C_{\mathrm{g}}\right)+\phi\rho_{\mathrm{w}}S_{\mathrm{w}}\left(R_{\mathrm{gre}}+R_{\mathrm{gde}}\right)=\frac{\partial}{\partial t}(\phi_{\mathrm{g}}\rho_{\mathrm{w}}S_{\mathrm{w}}C_{\mathrm{g}}+\rho_{\mathrm{r}}(1-\phi)C_{\mathrm{gad}}) \tag{5}$$

Salt: $$\nabla(C_s \frac{\rho_w K K_{rw}}{R_k \mu_w B_w}(\nabla p_w - \gamma_w \nabla D)) + \nabla\left(D_s \phi \rho_w S_w \nabla C_s\right) + q_s = \frac{\partial}{\partial t}(\phi \rho_w S_w C_s) \quad (6)$$

Where $\lambda_a = \frac{K_a}{\mu_a}$, a=o or w, ϕ_p and ϕ_g are the accessible pore volume coefficients of polymer and gel, C_p, C_c, C_g and C_s are the concentrations of polymer, crosslinker, gel, and salt, D_p, D_c, D_g and D_s are the diffusion coefficients of polymer, crosslinker, gel, and sal, R_{pre}, R_{cre} and R_{gre} are the concentrations of polymer, crosslinker, and gel consumed or produced by crosslinking reaction in a time unit, C_{pad}, C_{cad} and C_{gad} are the adsorption amounts of polymer, crosslinker, and gel on rock surfaces.

The auxiliary equations are:

Saturation equation: $$S_o + S_w = 1 \quad (7)$$

Capillary pressure equation: $$P_{cow} = P_o - P_w = P(S_w, \sigma_{wo}) \quad (8)$$

3. Processing of Parameters

3.1. Water viscosity

1) Viscosity without considering shear rate

The influence of threshold crosslinking concentration is considered for the processing of the viscosity of weak gel system [6-7]. When the concentration of the crosslinking system is lower than threshold crosslinking concentration, the empirical formula proposed by Flory-Huggins should be used; when the concentration of the injection system is higher than the threshold, the modified formula of Flory-Huggins (Equation (9)) should be used.

$$\mu_{gel}{}^{0} = \begin{cases} \mu_w\left(1 + b_1 C_p + b_2 C_p^2\right) & C_{gel} \le C'_{gel} \\ \mu_w\left[1 + b_1 C_p + b_2 C_p^2 + b_3\left(C_{gel} - C'_{gel}\right)^3\right] & C_{gel} > C'_{gel} \end{cases} \quad (9)$$

Where μ_{gelo} is the viscosity of the salt-less and shear-less crosslinking system, C'_{gel} is the threshold crosslinking concentration, b_1, b_2 and b_3 are coefficients.

2) Viscosity of salt-contained and shearing injection system

Quite a few factors would influence the viscosities of polymer and crosslinking system, for example the relative molecular weight, temperature, salinity, and mechanical shearing of polymer and inter crosslinking system polymer. The Meter equation (Equation (10)) describes the influence of shearing on the viscosity of polymer solution.

$$\mu_p = \mu_\infty + \frac{\mu^0 - \mu_\infty}{1 + \left(\frac{\dot{\gamma}}{\dot{\gamma}_{0.5}}\right)^{n-1}} \quad (10)$$

Where μ^0 is the viscosity of the polymer solution without shear rate, μ_∞ is the viscosity when the shear rate is infinite, $\dot{\gamma}$ is the shear rate, $\dot{\gamma}_{0.5}$ is the shear rate when $\mu = 0.5\mu^0$, n is the power law exponent of non-Newtonian fluid, and $1.0 \le n \le 1.8$.

When the influences of salinity and shear rate are considered: $\dot{\gamma} = \frac{268|u|}{\left[KK_{\rm rw}/(\phi S_{\rm w})\right]^{1/2}}$ (11)

The viscosities of polymer and gel are expressed by Equation (12) and (13), respectively.

$$\mu_{\rm p} = \mu_{\rm w} + \left(\mu_{\rm p}{}^{0} {\rm e}^{-a_1 C_{\rm se}} - \mu_{\rm w}\right) {\rm e}^{-a_2(1+a_3 C_{\rm se})\dot{\gamma}} \tag{12}$$

$$\mu_{\rm gel} = \mu_{\rm po} + \left(\mu_{\rm gel}{}^{0} {\rm e}^{-b_1 C_{\rm se}} - \mu_{\rm po}\right) {\rm e}^{-b_2(1+b_3 C_{\rm se})\dot{\gamma}} \tag{13}$$

Where $\mu_{\rm p}$ is the viscosity of the polymer solution when the influences of salinity and mechanical shearing are considered, $\mu_{\rm gel}$ is the viscosity of the crosslinking system solution when the influences of salinity and mechanical shearing are considered, $C_{\rm se}$ is the effective salinity, and a_1, a_2, a_3, b_1, b_2 and b_3 are coefficients.

By linear summation of the viscosity of each component with Equation (14), the viscosity of the compound solution could be obtained.

$$\mu_{\rm T} = f(\mu_{\rm w}, \mu_{\rm p}, \mu_{\rm gel}) \tag{14}$$

3.2. Relative permeability rates of oil and water phases

The relative permeability rates of oil and water phases can be calculated by Equation (15) and (16).

$$K_{\rm ro}(S_{\rm w}) = K_{\rm ro}(S_{\rm wc}) \cdot \left(\frac{1-S_{\rm w}-S_{\rm or}}{1-S_{\rm wc}-S_{\rm or}}\right)^{n_{\rm o}} \tag{15}$$

$$K_{\rm rw}(S_{\rm w}) = K_{\rm rw}(S_{\rm or}) \cdot \left(\frac{1-S_{\rm w}-S_{\rm wc}}{1-S_{\rm wc}-S_{\rm or}}\right)^{n_{\rm w}} \tag{16}$$

Calculate the logarithms of the two sides of the two equations above, substitute the measured actual relative permeability rates of oil phase and water phase, and the straight line slopes obtained after linear regression are the relative permeability rate factors $n_{\rm o}$ and $n_{\rm w}$ of oil phase and water phase, respectively.

3.3. Adsorption

The adsorption or retention of polymer and gel on the rock surfaces are the main factors reducing the stratums permeability [8]. The factors influencing the adsorption are mainly the type, concentration, and molecular size of the polymer and gel, as well as parameters of the stratum environment like temperature, salinity, rock type, clay content, permeability, and porosity. Assuming the adsorption of chemical agents is irreversible and follows the Langmuir adsorption law, the adsorption could be expressed by Equation (17-19).

$$C_{\rm pad} = C_{\rm padmax} \frac{a_1 C_{\rm p}}{1+b_1 C_{\rm p}} \tag{17}$$

$$C_{\rm cad} = C_{\rm cadmax} \frac{a_2 C_{\rm p}}{1+b_2 C_{\rm p}} \tag{18}$$

$$C_{\mathrm{gad}} = C_{\mathrm{gadmax}} \frac{a_3 C_{\mathrm{p}}}{1 + b_3 C_{\mathrm{p}}} \tag{19}$$

Where q_{pad}, q_{cad} and q_{gad} are the maximum adsorption capacities of polymer, crosslinker, and gel on rock surfaces, a_1, a_2, a_3, b_1, b_2 and b_3 are the adsorption equilibrium constants whose values are measured in labs.

3.4. Accessible pore volume

Since polymer and gel are both macromolecules, the produced gel can only pass through the pores with larger throats, and the pores with smaller throats are inaccessible. The porosities of the pores accessible by polymer and gel are ϕ_{p} and ϕ_{g}, respectively; and the inaccessible pore volume is defined as equation (20) [9].

$$IPV = \frac{\phi - \phi_{\mathrm{a}}}{\phi} \tag{20}$$

Then $$\phi_{\mathrm{a}} = (1 - IPV)\phi \tag{21}$$

Where a=p or a=g.

3.5. Residual resistance coefficient

The polymer in the gel solution would adsorb on the surface of the pores in oil layers and retain inside them, which would cause the decrease of the permeability rate of water phase. The residual resistance coefficient R_{k} is a measurement of the decrease in the permeability rate caused by the gel produced after the polymer solution flows through porous media and develops chemical reactions, its expression is as shown in Equation (22) [10].

$$R_{\mathrm{k}} = 1 + \frac{(R_{\mathrm{kmax}} - 1) b_{\mathrm{rk}} \times C_{\mathrm{p}}}{1 + b_{\mathrm{rk}} \times C_{\mathrm{p}}} \tag{22}$$

Where R_{kmax} is the maximum residual resistance coefficient, b_{rk} is an undetermined constant.

3.6. Crosslinking reaction

The crosslinking reaction between polymer and crosslinker could be expressed as [11]:

Polymer (P) + Crosslinker (C) → Gel (G)

Under certain reaction conditions, the following laws of chemical reaction dynamics could describe the crosslinking reaction rate [12-13]:

$$\frac{1}{C_{\mathrm{p}}^{0}} \cdot \frac{\mathrm{d}C_{\mathrm{p}}}{\mathrm{d}t} = -REC \cdot \left(C_{\mathrm{p}}\right)^{m} \cdot \left(C_{\mathrm{c}}\right)^{n} \tag{23}$$

$$\frac{1}{C_{\mathrm{c}}^{0}} \cdot \frac{\mathrm{d}C_{\mathrm{c}}}{\mathrm{d}t} = -REC \cdot \left(C_{\mathrm{p}}\right)^{m} \cdot \left(C_{\mathrm{c}}\right)^{n} \tag{24}$$

The reaction rates of polymer, crosslinker, and gel are as expressed by Equation (25), (26), and (27), respectively.

$$R_{\text{pre}} = -R_{\text{e}}\left(C_{\text{p}}^{\text{o}}\right)^{m+1}\left(C_{\text{c}}^{\text{o}}\right)^{n}\cdot\left[1+(m+n-1)R_{\text{e}}\left(C_{\text{p}}^{\text{o}}\right)^{m}\left(C_{\text{c}}^{\text{o}}\right)^{n}t\right]^{\frac{m+n}{m+n-1}} \tag{25}$$

$$R_{\text{cre}} = -R_{\text{e}}\left(C_{\text{p}}^{\text{o}}\right)^{n+1}\left(C_{\text{c}}^{\text{o}}\right)^{n}+1\left[1+(m+n-1)R_{\text{e}}\left(C_{\text{p}}^{\text{o}}\right)^{m}\left(C_{\text{c}}^{\text{o}}\right)^{n}t\right]^{\frac{m+n}{m+n-1}} \tag{26}$$

$$R_{\text{pre}} = -R_{\text{e}}\left(C_{\text{p}}^{\text{o}}+C_{\text{c}}^{\text{o}}\right)\left(C_{\text{p}}^{\text{o}}\right)^{m}\left(C_{\text{c}}^{\text{o}}\right)^{n}\left[1+(m+n-1)R_{\text{e}}\left(C_{\text{p}}^{\text{o}}\right)^{m}\left(C_{\text{c}}^{\text{o}}\right)^{n}t\right]^{\frac{m+n}{m+n-1}} \tag{27}$$

Where R_{e} is a constant for chemical reaction rate, its value is determined in labs or laws of chemical reaction dynamics, m and n are chemical reaction series, and $m \geq 1$, $n \geq 1$.

3.7. Degradation

The degradations of gel are mainly mechanical shearing, and chemical or thermal degradation [14]. Shear degradation mainly occurs because of the variation in velocity when the solution passes through pumps, pipes, perforations or enters the ground. Chemical degradation mainly refers to the inter-molecule chain breaking caused by the oxidation of the solution in stratums. Thermal degradation is decided by the thermal stability of polymer and gel in stratums.

For gels, the degradation rate R_{gde} could be expressed by Equation (28) [15].

$$R_{\text{gde}} = \frac{\mathrm{d}c_{\text{g}}}{\mathrm{d}t} = -K_{\text{gde}}\cdot C_{\text{g}} \tag{28}$$

Where K_{gde} is a degradation constant whose value is determined in labs.

3.8. Definite conditions of the model

1) Boundary conditions

The outer boundary of the model is closed boundary, *i.e.*, $\frac{\partial\varphi}{\partial n}\big|_{t=0}=0$ or constant pressure boundary. The inner boundary is line source (water injection well) and line congruence (production well). The boundary conditions of production well and water injection well are constant pressure or constant production.

2) Initial conditions

Initial conditions of the model could be the initial conditions when the reservoir is commissioned, or the oil-phase pressure, water-phase saturation, and the mass concentration distributions of each component when the reservoir is exploited into the end of a certain stage, $C_{\text{p}}\big|_{t=0}=0$, $C_{\text{g}}\big|_{t=0}=0$, $C_{c}\big|_{t=0}=0$, $C_{\text{s}}\big|_{t=0}=C_{\text{s}}$ (effective salinity of the original water in the stratum).

4. Solving of the Mathematical Model

The numerical discretization adopts the "finite difference" method to solve the mathematical model. The mass balance equations of each component are expressed by a series of discrete finite difference equations. The implicit solutions of these discrete non-linear simultaneous equations could obtain stable and long time steps, and adopting adaptive implicit method could accelerate the simulation time and lower the demands on memory.

IMPES method is to solve the variables in the equation set step-by-step. Usually, the pressure should be calculated first with implicit method, and then the saturation is calculated with explicit method. The detailed process is described as below.

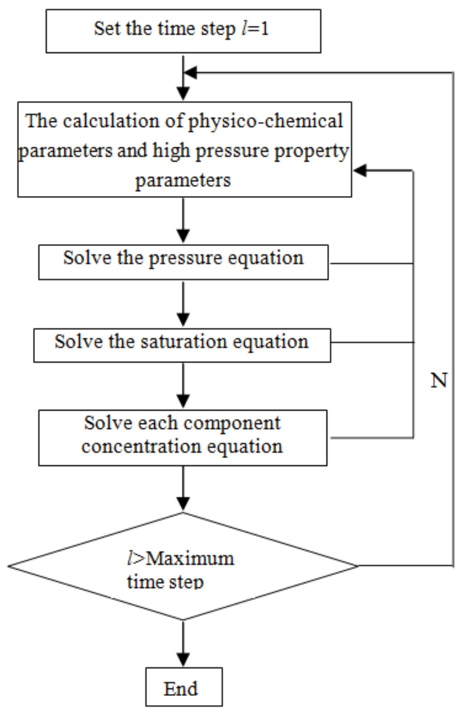


Figure 1. The thought of IMPES method solving

5. Application of Numerical Simulation for Deep Profile Control with Gel

During the initial ASP slugging stage of the industrialized ASP flooding block of Xingbei development zone of Daqing oil field, due to the incompatibility of the injection technology and process, the performance of the injection system is poor. After process reformation and continuous follow-up adjustments, the response situation of the block is improved to a certain extent. However, unbalanced response situation is still outstanding in the block, and some production wells have bad response situations. This type of wells concentrates near the water injection well of the basic well pattern, where macro-pores exist at the bottom oil layer and low-efficiency or invalid circulations are serious. The high-permeability layers of these wells have relative fluid adsorption of up to 69.2%, while the fluid adsorption thickness ratio is only 23.9%; the injection strength of these wells reaches 15.6m^3/d.m, which is 9.4m^3/d.m greater than the average injection strength of the whole block. In addition, the oil layer growth of the injection wells in the block is predominantly full zone growth, with low potential of separated injection, thus deep profile control is needed. However, currently there is not any successfully profile control precedent in alkali system. Therefore, profile control technology in polymer flooding needs to be studied in order to guide the development of profile control approach for ASP flooding, improve the utilization of chemical agents, and enhance the overall production of the block. In-door experiments have helped optimize the formula of deep profile control with gel, and using numerical simulation technology, we performed optimization on the injection approaches.

5.1 Geological model

In order to simulate the development effect of intra-flooding deep profile control with gel in ASP flooding, we established an ideal model using the software we created. The geological model is vertically composed by three layers with permeability of $300\times10^{-3}\mu m^2$, $500\times10^{-3}\mu m^2$ and $800\times10^{-3}\mu m^2$ from top to bottom, forming a positive rhythm reservoir. From top to bottom, the effective thicknesses of the layers are 1.5m, 2m, and 2.5m, the porosities of the layers are 0.26, 0.28, and 0.3, and the oil saturation of the layers are all 0.74. A Cartesian coordinate grid system is established, with 21 grids on both X and Y direction, step length of grid is 10.6m. Five wells are distributed in the oil layers in a 5-spot area well pattern; four of the wells are injection wells and one is production well, and the distance between injection wells and the production well is 150m. The plane grid division is as shown in Figure 2.

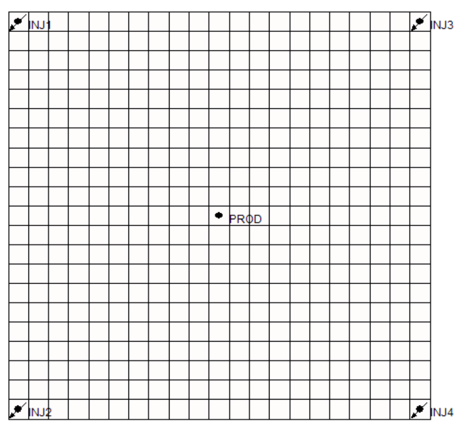


Figure 2. The grid subdivision schemes of geological model

5.2. Optimization of injection parameters for deep profile control with gel

With the established ideal model, we performed optimization on the size of injected gel and the slug combination, and then compared the development effects of the optimized approach, water flooding, and ASP flooding. The injection rate of both water flooding and ASP flooding is 0.2PV/a, and the injection rate of gel is 0.18PV/a. The ASP formula is: polymer with concentration of 2000mg/L, NaOH with concentration of 1.2%, and surfactant with concentration of 0.3%.

5.2.1 Optimization of slug combination: In the site construction of ASP flooding, the injected alkali has a large concentration, usually 1.2%wt. This way, part of the alkali in the injected ASP flood fluid would adsorb on rock surface. When gel is injected afterward, these alkalis would weaken the performance of the gel, and the gel front would contact the ASP fluid, which would also weaken its performance. By taking these two types of impacts into consideration, we added polymer pre-slug at the gel front and then performed numerical simulation. The polymer pre-slug could dilute the residual alkali in the stratum, prevent the gel from contacting the ASP fluid, thereby ensuring good performance of the gel in the profile control process. Meanwhile, we also designed trail-slug and analyzed its influence on the development effect of deep profile control with gel.

1) Influence of the size of polymer pre-slug on the development effect

Polymer pre-slugs of 0.005PV, 0.01PV, and 0.015PV were designed, the approaches are detailed below.

Approach 1: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.035PV of gel + 0.2PV of ASP + post water flooding until Water cut reaches 98%;

Approach 2: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.005PV of polymer (with concentration of 2000mg/L) + 0.035PV of gel + 0.2PV of ASP + post water flooding until Water cut reaches 98%;

Approach 3: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.01PV of polymer (with concentration of 2000mg/L) + 0.035PV of gel + 0.2PV of ASP + post water flooding until Water cut reaches 98%;

Approach 4: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.015PV of polymer (with concentration of 2000mg/L) + 0.035PV of gel + 0.2PV of ASP + post water flooding until Water cut reaches 98%.

The numerical simulation result of the four approaches is as shown in Table 1.

Table 1. Development effects of the approaches

Approach	Recovery rate (%)	Recovery rate increment comparing to recovery rate without polymer pre-slug (%)
Approach 1	73.77	/
Approach 2	74.08	0.31
Approach 3	74.33	0.56
Approach 4	74.39	0.62

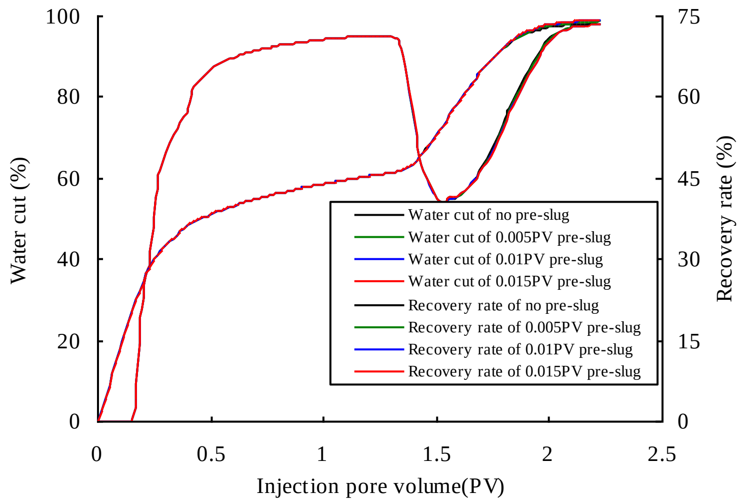


Figure 3. Comparison of recovery rate and water cut of each approach

It can be seen that with the increase of the size of the polymer pre-slug, the recovery rate increases as well; however, after the size of the polymer pre-slug reaches 0.01PV, the increase in the size has little influence on the recovery rate. When there is no polymer pre-slug, the recovery rate is 73.77% when the Water cut reaches 98%. When polymer pre-slug of 0.005PV is added, the recovery rate increased by 0.31%. When the size of the polymer pre-slug is increased to 0.01PV, the recovery rate further increased by 0.25%. When the size is increased to 0.015PV, the recovery rate further increased by 0.06% only. Considering from economic and development effect views, the polymer pre-slug of 0.01PV is chosen.

2) Influence of the concentration of polymer pre-slug on the development effect

Based on the optimization of polymer pre-slug, pre-slug of 0.01PV is chosen. Three approaches with concentrations of polymer slug as 1500mg/L, 2000mg/L, and 2500mg/L are designed to analyze the influence of the concentration of polymer pre-slug on the development effect of deep profile control with gel. The approaches are detailed below.

Approach 1: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.01PV of polymer (with concentration of 1500mg/L) +0.035PV of gel +0.2PV of ASP + post water flooding until Water cut reaches 98%;

Approach 2: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.01PV of polymer (with concentration of 2000mg/L) +0.035PV of gel +0.2PV of ASP + post water flooding until Water cut reaches 98%;

Approach 3: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.01PV of polymer (with concentration of 2500mg/L) +0.035PV of gel +0.2PV of ASP + post water flooding until Water cut reaches 98%.

The numerical simulation result of the three approaches is as shown in Table 2.

Table 2. Development effects of the approaches

Approach	Recovery rate （%）	Recovery rate increment comparing to recovery rate without polymer pre-slug （%）
Approach 1	74.06	0.29
Approach 2	74.33	0.56
Approach 3	74.37	0.60

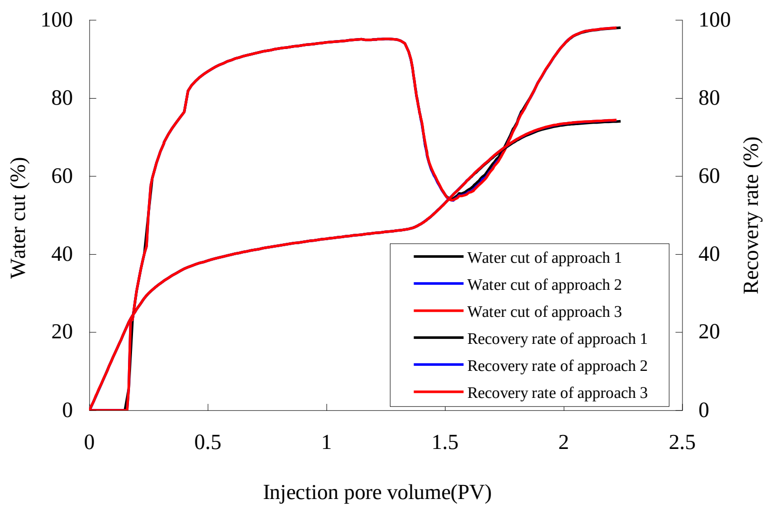


Figure 4. Comparison of recovery rate and water cut of each approach

It can be seen that that with the increase in the concentration of the polymer pre-slug, the recovery rate increases as well. When the concentration is 1500mg/L, the recovery rate is 74.06%, which is 0.29% higher than the recovery rate without polymer pre-slug; when the concentration increases to 2000mg/L, the recovery rate increased by 0.35% comparing with that when the concentration is 1500mg/; when the concentration is 2500mg/L, the recovery rate further increased by 0.04% only. Overall considering from economic and effective perspectives, the concentration of polymer pre-slug is determined as 2000mg/L.

Combining the analysis in the two sections above, the concentration of the polymer pre-slug for deep profile control with gel determined as 2000mg/L, and the size of the pre-slug is decided as 0.01PV.

3) Influence of trail-slug on the development effect

Based on the previous analysis, trail-slug is added on the basis of pre-slug with the concentration of 2000mg/L and the size of 0.01PV, two approaches are designed for the analysis of the influence of trail-slug on the effect of deep profile control with gel.

Approach 1: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.01PV of polymer (with concentration of 200mg/L) +0.035PV of gel +0.2PV of ASP + post water flooding until Water cut reaches 98%;

Approach 2: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.01PV of polymer (with concentration of 2000mg/L) +0.035PV of gel +0.2PV of ASP + 0.01PV of polymer (with concentration of 2000mg/L) + post water flooding until Water cut reaches 98%.

The numerical simulation result of the three approaches is as shown in Figure 5.

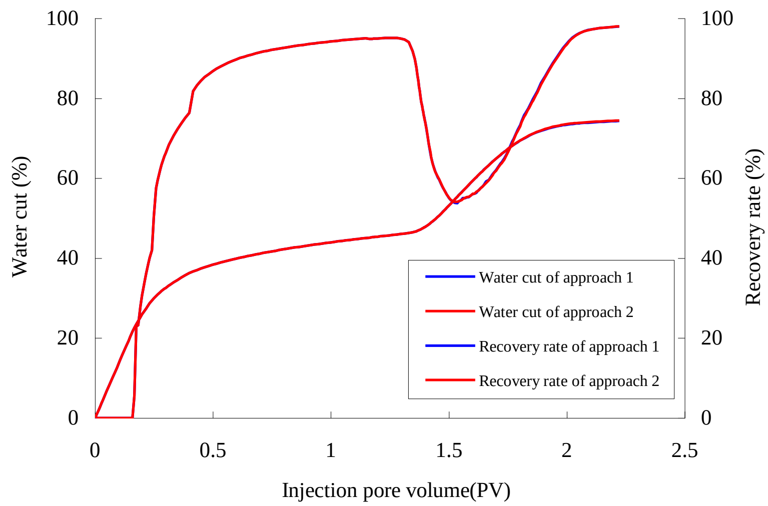


Figure 5. Comparison of recovery rate and water cut of each approach

It can be seen that the addition of 0.01PV of trail-plug has little influence on the effect of gel deep profile control. The recovery rate without trail-plug when the Water cut reaches 98% is 74.33%, while the recovery rate with 0.01PV of trail-plug is 74.46%. The increment of 0.13% has little influence on the effect of deep profile control with gel.

Based on the above analysis, pre-slug has significant influence on development effect, whereas trail-plug has little. The reason is that the polymer pre-slug dilutes the residual alkali in the stratum and prevents the gel from contacting the ASP fluid, thereby ensuring good performance of the gel in the profile control process. Therefore, the optimal slug combination for gel flooding is to add 0.01PV of polymer solution with concentration of 2000mg/L before gel flooding.

5.2.2. Slug size optimization for deep profile control with gel: Three approaches with different sizes of slugs are designed as below.

Approach 1: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.01PV of polymer (with concentration of 200mg/L) +0.02PV of gel +0.2PV of ASP + post water flooding until Water cut reaches 98%;

Approach 2: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.01PV of polymer (with concentration of 200mg/L) +0.035PV of gel +0.2PV of ASP + post water flooding until Water cut reaches 98%;

Approach 3: water flooding until Water cut reaches 95% + 0.2PV of ASP + 0.01PV of polymer (with concentration of 200mg/L) +0.05PV of gel +0.2PV of ASP + post water flooding until Water cut reaches 98%.

The simulation result of the three approaches is as shown in Table 3.

Table 3. Development effects of the approaches

Approach	Recovery rate（%）	Recovery rate increment comparing to ASP flooding（%）
Approach 1	72.95	3.20
Approach 2	74.33	4.58
Approach 3	74.74	4.99

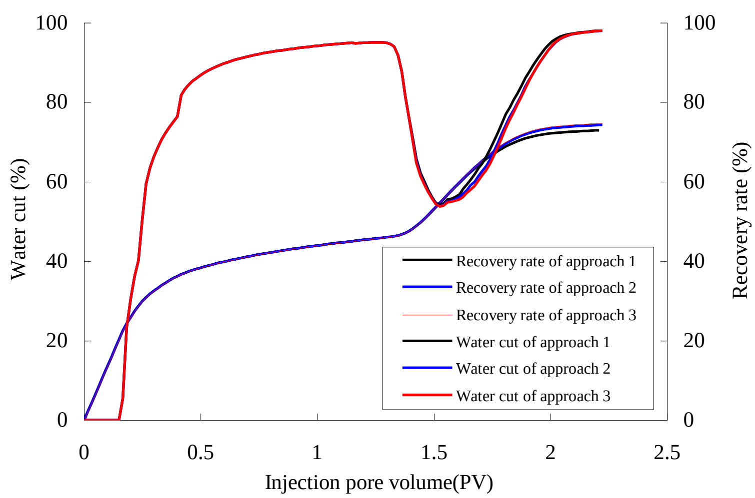


Figure 6. Comparison of recovery rate and water cut of each approach

It can be seen that when of the slug size of injected gel increases, the recovery rate increases as well; however, after the size of the slug reaches 0.035, the increase has little influence on the recovery rate. When the slug size is 0.02PV, the recovery rate increased by 3.20% comparing to ASP flooding; when the slug size is 0.035PV, the recovery rate further increased by 1.38%; when the slug size is 0.05PV, the recovery rate only further increased by 0.41%. Therefore, gel slug of 0.035PV is the optimal choice.

Based on the analysis on the slug combination and slug size optimization for deep profile control with gel, polymer pre-slug of 2000mg/L and 0.01PV+0.035PV of gel is the optimal choice for intra-flooding deep profile control with in ASP flooding.

5.3. Evaluation of deep profile control with gel effects

In order to evaluate the profile control effects of gel in ASP flooding, we compared the deep profile control with gel, water flooding, and ASP flooding with the following specifics.

Water flooding: Water flooding until Water cut reaches 98%;

ASP flooding: Water flooding until Water cut reaches 95% + 0.4PV of ASP + post water flooding until Water cut reaches 98%;

ASP flooding with deep profile control of gel: Water flooding until Water cut reaches 95% + 0.02PV of ASP + 0.01PV of polymer (with concentration of 2000mg/L) + 0.035PV of gel + 0.2PV of ASP + post water flooding until Water cut reaches 98%.

The numerical simulation result of the three flooding approaches is as shown in Table 4.

Table 4. Development effects of the three flooding approaches

Approach	Lowest Water cut (%)	Decrement (%)	Recovery rate (%)	Recovery rate increment comparing to water flooding (%)
Water flooding	/	/	51.33	/
ASP flooding	56.25	38.75	69.75	18.42
ASP and gel	53.84	41.16	74..33	23.00

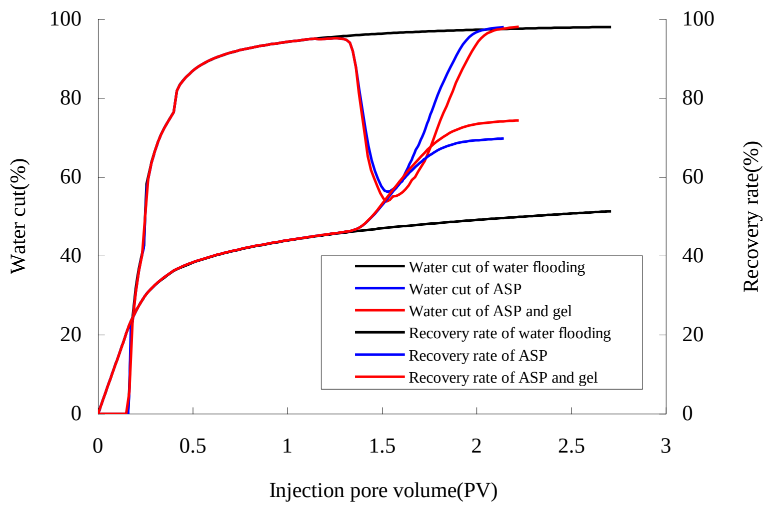


Figure 7. Comparison of development effects of the three oil displacement approaches

According to the numerical simulation result, the addition of 0.035PV of deep profile control with gel in ASP flooding could increase the recovery rate of water flooding by 23%, and increase that of ASP flooding by 4.58%. The lowest Water cut is 53.84%, which reduced by 41.46% comparing with the Water cut before chemical flooding, and 2.41% comparing with the Water cut before ASP flooding.

5.4. Analysis of the mechanics of deep profile control with gel

In order to study the mechanics of deep profile control with gel, we analyzed the fluid production, Water cut, and post-displacement oil saturation of individual well at high, moderate, and low permeability, respectively. For layers of different permeability in individual well, Figure 8-10 present the calculated fluid production, Figure 11-13 present the calculated Water cut, and Figure 13-15 present the calculated post-displacement oil distribution.

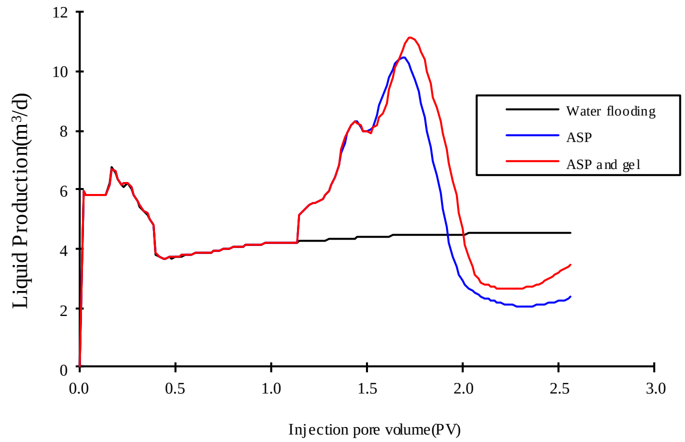


Figure 8. Fluid productions in low-permeability layers

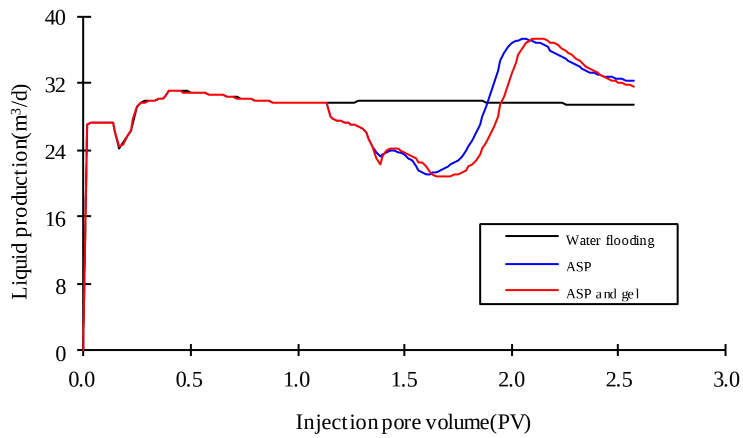


Figure 9. Fluid productions in moderate-permeability layers

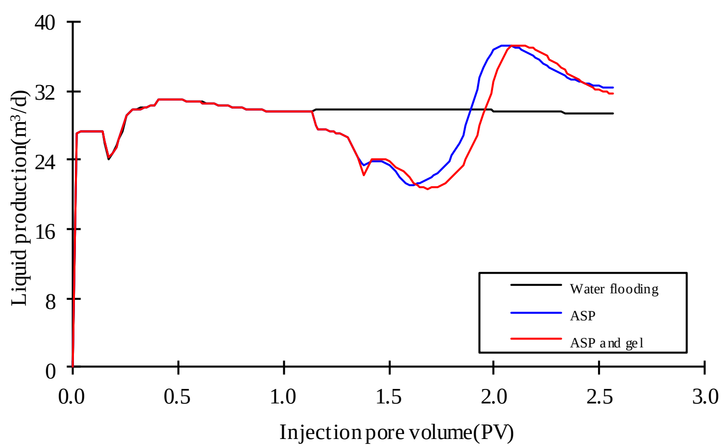
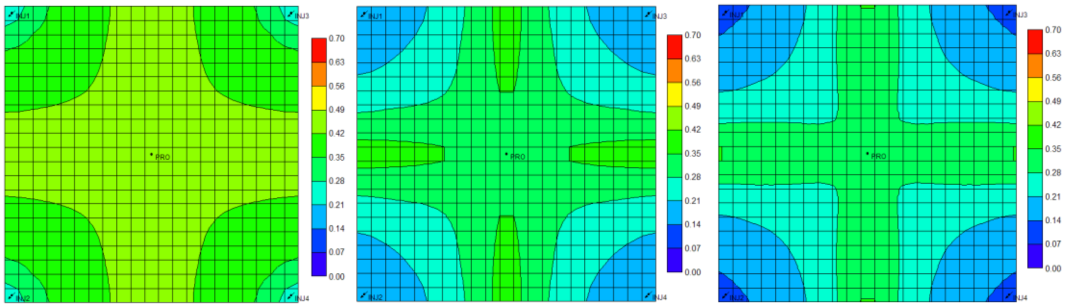
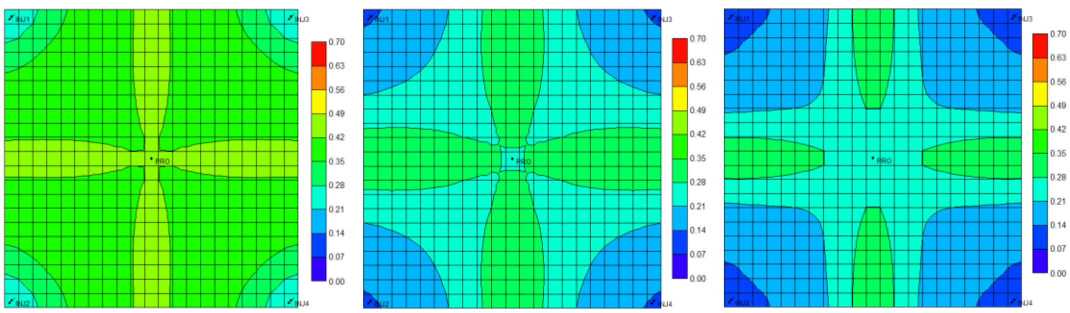


Figure 10. Fluid productions in high-permeability layers



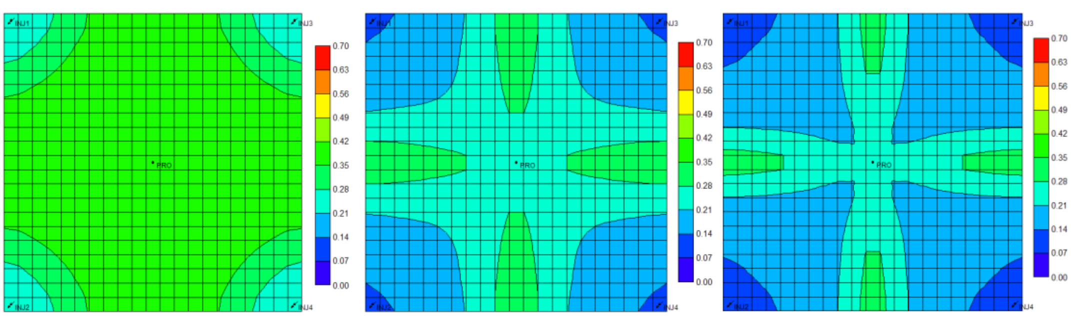
Water flooding ASP flooding ASP and gel

Figure 11. Post-displacement oil distributions of three oil displacement approaches in low-permeability layers



Water flooding ASP flooding ASP and gel

Figure 12. Post-displacement oil distributions of three oil displacement approaches in moderate-permeability layers



Water flooding ASP flooding ASP and gel

Figure 13. Post-displacement oil distributions of three oil displacement approaches in high-permeability layers

It can be seen from Figure 8-10 that serious channeling of the displacing fluid along high-permeability layers occurred in water flooding due to the unfavorable mobility ratio, the moderate- and low-permeability layers are not displaced well. For ASP flooding, the increase of water-phase viscosity adjusted the profile to a certain extent; comparing with water flooding, the fluid adsorption of high-permeability layers decreased because of the increase in flow resistance, forcing the displacing fluid to enter the moderate- and low-permeability layers, which improves the oil displacement effect in these layers. After adding deep profile control with gel in ASP flooding, the profile adjustment effect is improved, and the high-permeability layers are better slugged; when the crosslinking system is injected to the oil layer, the displacing fluid that enters the high-permeability layers is reduced, stimulating more displacing fluid to enter moderate- and low-permeability layers, thereby improving the oil displacement effect. Seen from Figure 11-13, the oil saturation of low-permeability layers barely changed after water flooding, which means the oil is basically not displaced, whereas the oil in high-permeability layers are well displaced. As for ASP flooding, the increase of the viscosity of the injected fluid has certain profile adjustment ability, which improved the producing degree of the oil in low-permeability layers. After adding 0.035PV of deep profile control with gel in ASP flooding, the producing degree of low-permeability layers is further improved. According to the analysis of the simulation result, the deep profile control with gel in ASP flooding could improve the profiles and enhance the oil recovery rate.

6. Conclusions

1) In this study, a mathematical model for three-dimensional two-phase six-component deep profile control with weak gel was established based on the mechanics of deep profile control with weak gel. This model takes diffusion, crosslinking reaction, adsorption, degradation and other physical or chemical phenomena into consideration. A numerical simulation software for deep profile control with gel was created with FOR99 programming language.

2) Based on the geological features of the ASP flooding areas of Daqing oil field, an ideal model was established using the created software. With this model, we performed optimization on the slug combination and slug size for the deep profile control with gel in the ASP flooding areas of Daqing oil field and obtained the optimal injection approach. Our study showed that polymer pre-slug has greater influence on the development effect, while trail-slugs have little. The reason is that the polymer pre-slug would dilute the residual alkalis in the stratum and prevent the gel from contacting the ASP fluid, so that the good performance of gel during the profile controlling process is ensured.

3) The created software was used for the analysis of the mechanisms of deep profile control with gel. The analysis demonstrated that in ASP flooding, the employment of deep profile control with gel could improve the profile modification effect, and strengthen the plugging of high-permeability layers. After the crosslinking system is injected into oil layer, less displacing fluid could enter the high-permeability layers, forcing more sweeping fluid to enter moderate or low-permeability layers, thereby the oil displacement effect is improved. After the addition of deep profile control with gel, the producing degree of low-permeability layers is further improved.

Acknowledgements

This work is supported by the National Natural Science Foundation of China under Grant No.51074034.

References

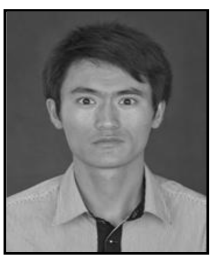
[1] D. Y. Yin, H. Pu and Y. X. Wu, "Numerical simulation of imbibition oil recovery for low permeability fractured reservoir", Chinese Journal of Hydrodynamics, vol. 4, **(2004)**, pp. 19.

[2] D. Y. Yin and H. Pu, "Numerical Simulation Study on Surfactant Flooding for Low Permeability Oilfield in The Condition of Threshold Pressure", Journal of Hydrodynamics, vol. 4, **(2008)**, pp. 20.

[3] D. Y. Yin, Y. G. Guo and W. M. Huang, "The determination of reasonable cycle time for bailing oil production in low permeability field", The 21st session of the national seminar on hydrodynamics and the 8th

national conference on hydrodynamics and on both sides of the ship and ocean engineering hydrodynamics seminar, **(2008)** August 562-567; China.
[4] H. Q. Jiang, W. Liu, M. Yuan and M. R. Sun, "Numerical Simulation Research on Times Profile Control", Oil Drilling & Production Technology, vol. 5, **(2003)**, pp. 25.
[5] W. Liu, "The Numerical Simulation Research of Multi round Profile Control in the Reservoir of High Water", Chinese Journal of Engineering Mathematics, vol. 4, no. 22, **(2005)**, pp. 580-584.
[6] G. Chen, G. Zhao and Y. L. Ma, "Mathematical Model of Polymer Linked Profile Control Enhanced Oil Recovery", Journal of Tsinghua University (Science and Technology), vol. 12, no. 44, **(2004)**, pp. 1607-1609.
[7] G. Zhang, Q. H. Feng, D. K. Tong, Y. Liu, S. D. Liu and Y. B. Chen, "Mathematical Model of Mobile Gel for Deep Profile Control and Oil Displacement and Fast Solution Methods", Petroleum Geology and Recovery Efficiency, vol. 04, no. 15, **(2008)**, pp. 56-58.
[8] X. C. Wu, W. Y. Zhu, Q. K. Ma, Y. Zhang, H. Chen and Y. P. Liu, "Study on Nonlinearity Seepage Characteristic and Mathematical Model of Movable Gel", Oil Drilling & Production Technology, vol. 28, no. 05, **(2006)**, pp. 43-45.
[9] Q. H. Feng, G. Zhang, Y. Tao and W. D. Wu, "Study of Fast Simulation Method for Flowing Gel Driving", Journal of China University of Petroleum (Edition of Natural Science), , vol. 6, no. 30, **(2006)**, pp. 64-70.
[10] B. Xu and L. S. Cheng, "Numerical Simulation of Deep profile control with Weak Gel", Chinese Journal of Computational Physics, vol. 2, no. 22, **(2005)**, pp. 164-170.
[11] Y. Kyung, J. -w. Kim, S. -B. Jung and K. -H. Eom, "Optimal Control Method for a Hydroelec-tric Power Development in Multi Level Dams", International Journal of Control and Automation, vol. 3, no. 13, **(2009)**.
[12] M. Li and Z. J. Kang, "Research and Application of Numerical Model of Profile Control In-depth", Petroleum Geology & Oilfield development in Daqing, vol. 3, no. 23, **(2004)**, pp. 77-80.
[13] K. P. Song, "Fluid Poromechanics in Polymer Flooding", Beijing: Petroleum Industry Press, **(1999)**.
[14] T. L. Chen, X. J. Zhou, F. P. Tang and S. Y. Wang, "Recovery Enhance Technology with Deep profile control with Weak Gel", Beijing: Petroleum Industry Press, **(2006)**.
[15] R. D. Kokate and L. M. Waghmare, "Review of Tuning Methods of DMC and Performance Evaluation with PID Algorithms on a FOPDT Model", International Journal of Control and Automation, vol. 4, no. 95, **(2011)**.

Authors



Zhou Yazhou

He received the master's degree in Oil and Gas Field Development from Northeast Petroleum University, China in 2009, and received the bachelor's degree in Petroleum Engineering from Daqing Petroleum Institute, China in 2005. Currently, he is a PhD Candidate in Oil and Gas Engineering at Northeast Petroleum University. His research interests include reservoir numerical simulation, theory and technology of oil and gas field development.

Yin Daiyin

He received his PhD in Oil and Gas Field Development Engineer from Daqing Petroleum Institute, China in 2001. He received his bachelor degree in Reservoir Engineering and master degree in Oil and Gas Field Development Engineer from Daqing Petroleum Institute, China in 1988 and 1993 respectively. And he was a Post-Doc of Institute of Mechanics, Chinese Academy of Sciences. Currently, he is a professor in Department of Oil and Gas Field Development Engineer in Northeast Petroleum University, China. His research interests include reservoir geological modeling, numerical simulation and dynamic analysis on the development of oilfield.

