PETROLEUM EXPLORATION AND DEVELOPMENT
Volume 44, Issue 2, April 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: PETROL. EXPLOR. DEVELOP., 2017, 44(2): 286–293.

RESEARCH PAPER

Prediction method of produced polymer concentration based on interwell connectivity

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Abstract: To forecast some key parameters of produced liquid containing polymer, including the time of polymer output, polymer concentration, a polymer concentration prediction method based on interwell connectivity methodology was established, its prediction results were compared with those from numerical simulation software, and it has been used in a case study. On the basis of water flooding interwell connectivity model, a polymer flooding production performance prediction model considering the viscosity, concentration, adsorption and water-phase permeability reduction factor of polymer was built. Compared with the traditional numerical simulation, the pressure equations in this model have lower dimension, and it inverses the interwell conductivity and connected volume through automatic history matching, enhancing calculation speed and precision significantly. The calculation model was used to the history matching of a homogeous reservoir model with 1 injector and 4 producers, and the comparison of its results and the results from numerical simulation software shows the model is reliable and accurate. Moreover, sensitivity analysis of major model parameters reveals that the increase of water-phase permeability reduction factor, injected polymer concentration and pore volume injected and early polymer injection time can improve oil recovery. The real reservoir application shows the model can predict the change of produced polymer concentration of different development schemes accurately.

Key words: interwell connectivity; produced polymer concentration; polymer flooding; calculation model

Introduction

A large quantity of produced liquid is difficult to dispose in offshore polymer flooding field with limited platform space and the oil sludge with polymer may affect oilfield regular production. The key to solve this problem is to accurately predict the yield of sludge with polymer, and sludge with polymer production rate is closely related to produced polymer concentration so the produced polymer concentration should be predicted precisely. Review of published literatures shows that many factors, including geological static factors like sedimentary microfacies, reservoir heterogeneity, reservoir connectivity, and developing dynamic factors like well spacing, completion degree of well pattern, polymer injection rate et, al[1–4]. Therefore, predicting polymer concentration is difficult and with low accuracy, and there is no mature method available.

The polymer flooding developing dynamic prediction methods commonly used are field experiment method, numerical simulation method, statistical model method and analogy method[5–9]. The field experiment method mainly analyzes polymer breakthrough features based on produced polymer and geologic features of individual blocks, so the rule is regional and difficult to apply in other blocks. The traditional numerical simulation method mainly inverse reservoir geological model through history matching, and then get polymer concentration at all wells from production performance prediction. This method takes into account a wide range of factors and has powerful prediction capacity, but with cumbersome history matching work and huge computation, and the geological parameters from fitted modifying have strong uncertainty, making it difficult to ensure the accuracy of prediction results. Statistical model method with simple calculation is too idealized so its prediction results are not reliable. Furthermore, onshore oilfields and offshore oilfields have quite different reservoir situations and polymer injected conditions, so polymer production rules of offshore oilfields can not be simply got from analogy of onshore oilfields.

Therefore, based on the water flooding interwell connectivity model[10–15] which has been applied to many oilfields, we establish the produced polymer concentration prediction mod-

Received date: 15 Aug. 2016; **Revised date:** 16 Jan. 2017.
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Foundation item: Supported by the China National Science and Technology Major Project (2016ZX05025-003); State Key Laboratory of Offshore Oil Exploitation (CCL2015RCPS0223RNN).

model of polymer flooding. The model has been verified with synthetic model, and sensitivity analysis of main parameters has been applied, then the model has been used in real reservoirs in this study.

1. Establishment of model

Based on the water flooding interwell connectivity model put forward by Zhao Hui et al[10,14], a polymer flooding model has been built by considering the viscosity, concentration, adsorption of polymer solution, and reduction factor of water phase permeability. Based on the idea of interwell connectivity, the reservoir is simplified into a series of connected units characterized by average conductivity T_{ijk} and connected volume V_{ijk}, the former indicates flow capacity of the unit, and the latter reflects the material basis of the unit.

Based on material balance equation under formation conditions, for the well i:

$$\sum_{k=1}^{N_1}\sum_{j=1}^{N_\mathrm{w}} T_{ijk}(t)\left[p_j(t)-p_i(t)\right]+q_i(t)=\frac{\mathrm{d}p_i(t)}{\mathrm{d}t}\sum_{k=1}^{N_1} C_{\mathrm{t}k}V_{\mathrm{p}ik}(t) \tag{1}$$

Eq.1 was discretized with the implicit difference method to get the pressure equations below:

$$\begin{bmatrix} p_1^{n-1} \\ p_2^{n-1} \\ \vdots \\ p_{N_\mathrm{w}}^{n-1} \end{bmatrix} = \begin{bmatrix} \psi_1+1 & -\omega_1 T_{12}^n & \cdots & -\omega_1 T_{1N_\mathrm{w}}^n \\ -\omega_2 T_{21}^n & \psi_2+1 & \cdots & -\omega_2 T_{2N_\mathrm{w}}^n \\ \vdots & \vdots & \cdots & \vdots \\ -\omega_{N_\mathrm{w}} T_{N_\mathrm{w}1}^n & -\omega_{N_\mathrm{w}} T_{N_\mathrm{w}2}^n & \cdots & \psi_{N_\mathrm{w}}+1 \end{bmatrix} \times \begin{bmatrix} p_1^n \\ p_2^n \\ \vdots \\ p_{N_\mathrm{w}}^n \end{bmatrix} - \begin{bmatrix} \zeta_1 \\ \zeta_2 \\ \vdots \\ \zeta_{N_\mathrm{w}} \end{bmatrix} \tag{2}$$

After solving the well-point pressure p_i through Eq.2, then flow distribution between well points can be calculated by differential pressure and average conductivity. Considering underground fluid flow reverse caused by well shutdown and convert, Eq.3 is used to calculate the derivative of the water cut, and then the water saturation at each well point is calculated by using interpolation method.

$$f_\mathrm{w}'\left(S_{\mathrm{w}ijk}^n\right)=\min\left[f_\mathrm{w}'\left(S_{\mathrm{w}jk}^n\right)+\frac{1}{F_{\mathrm{v}ijk}^n}, f_\mathrm{w}'\left(S_{\mathrm{w}ik}^{n-1}\right)\right] \tag{3}$$

After obtaining the pressure, flow rate and water saturation of the well points, the polymer concentration distribution is obtained by solving balance equation of polymer concentration. The polymer flooding involves the percolation process between oil phase and water phase, containing polymer, the non-Newtonian flow effect of macromolecule polymers and adsorption / retention effect in porous medium will affect the relative permeability. The experimental study on relative permeability curve of polymer flooding[16] has shown that, compared with water flooding, polymer flooding has much lower residual oil saturation, higher water saturation at isoosmotic point, and much higher bound water saturation after polymer injection slug.

Because of the homogeneity inside interwell unit, the polymer concentration is calculated by simulating one-dimensional linear polymer flooding model considering water phase features of polymer flooding. The connected unit between the well i and the well j are divided into homogeneous m grids, the flow rate inside the connected unit is Q_{ij}, the porosity is φ, and the grid volume is ΔV, and the compressibility of the rock is ignored.

Then the material balance equation of the polymer concentration for grid r is given by Eq.4:

$$\left(C_r^n S_\mathrm{w}^{n-1} - C_r^{n-1} S_\mathrm{w}^{n-1}\right)\phi\Delta V = \left(C_{r-1}^{n-1} - C_{r+1}^{n-1}\right)Q_{ij}\Delta t - \hat{C}(1-\phi)\Delta V \tag{4}$$

Polymer concentration expression can be obtained from reorganization of Eq.4:

$$C_r^n = \frac{\left(C_{r-1}^{n-1} - C_{r+1}^{n-1}\right)Q_{ij}\Delta t}{S_\mathrm{w}^{n-1}\phi\Delta V} - \frac{\hat{C}(1-\phi)}{S_\mathrm{w}^{n-1}\phi} + C_r^{n-1} \tag{5}$$

Based on interwell connectivity model, for the k_{th} layer of the well i, the material equilibrium equation of the polymer concentration is given as:

$$\sum_{j=1}^{N_\mathrm{w}} S_{\mathrm{w}ijk}^{n-1} V_{\mathrm{p}ik}\left(C_{ijk}^n - C_{ijk}^{n-1}\right) = \sum_{j=1}^{N_\mathrm{w}}\left(C_{ijk}^{n-1} Q_{\mathrm{I}ijk}^{n-1}\Delta t - C_{ijk}^{n-1} Q_{\mathrm{O}ijk}^{n-1}\Delta t - \hat{C}_{ijk}^{n-1} V_{\mathrm{p}ik}\right) \tag{6}$$

Suppose that the adsorption of polymer is instantaneous, according to the Langmuir isotherm adsorption law, the adsorption amount of polymer at a certain concentration in the reservoir can be calculated by the following equation[17–20]:

$$\hat{C}_{ijk}^{n-1} = \frac{aC_{ijk}^{n-1}}{1+bC_{ijk}^{n-1}} \tag{7}$$

In the Eq.7, a and b are obtained by experiment. After getting the polymer concentration in each layer of each well point, the viscosity of the polymer solution and the permeability reduction factor of the water phase after polymer injection can be worked out, and then the flow rate at each well point can be calculated.

$$\mu_1 = \mu_\mathrm{w}\left(1+\alpha C+\beta C^2+\gamma C^3\right) \tag{8}$$

$$R_k = 1+\hat{C}_{ijk}\left(R_{\max}-1\right) \tag{9}$$

$$f_\mathrm{w} = \frac{K_\mathrm{rw}}{\mu_1 R_k}\left(\frac{K_\mathrm{rw}}{\mu_1 R_k}+\frac{K_\mathrm{ro}}{\mu_\mathrm{o}}\right)^{-1} \tag{10}$$

In the Eq.8, *α, β, and γ* are obtained by experiment[21]. In Eq.9, $R_{\max}$, the maximum permeability reduction factor, is difficult to calculate, so it is determined by experimentation[22].

Compared with traditional numerical simulation method, the pressure equations in the polymer model proposed in this paper have lower dimension equal to the number of wells (Eq.2), furthermore, the water saturation tracking takes connected unit as objective, and is solved by semi-analytical method, so this method requires less computational time, and is fast and stable in computation. The more complete the well