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A novel model and sensitivity analysis for viscoelastic polymer flooding in offshore oilfield

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ABSTRACT

Polymer flooding has been widely used in petroleum industry. With the development of theory and technology, some problems in the existing models of polymer flooding appear during simulation. Based on the characteristics of polymer and offshore oilfield such as viscoelasticity, degradation effect and strong salt-sensitive effect, a novel model of viscoelastic polymer flooding is built, and the validation is verified. After comparing the distributions of effective viscosity and residual oil of taking account of elasticity and taking no account of elasticity, it is used to investigate the effects of injection rate, polymer molecular weight, salinity, degradation rate and well space.

1. Introduction

Polymer flooding is an enhanced oil recovery technology that can efficiently recover the remaining oil by injecting new displacement agent while injecting water to maintain the reservoir pressure. The injected polymer can increase the viscosity of water, and decrease the water-phase relative permeability, which will induce to the decrease of the mobility ratio of water to oil, increase the sweep volume, and enhance oil recovery [1]. The flow of rheologically polymer solution through porous media is a research area with a great variety of practical applications, such as secondary and tertiary oil recovery operations [2,3]. Since 1970s, many experts have recognized viscoelastic effects of polymer liquids [4–6]. What is more, the polymer solution shows nonlinear flow feature because of the viscoelastic property, and it is not a kind of simple shear-thinning fluid or a Newtonian one [7–9]. Many studies have shown that the polymer flooding also can significantly increase the viscosity of water phase and improve microscopic-oil displacement efficiency because of the viscoelastic properties of polymer molecules [10–12]. And as a mature EOR technology, polymer flooding is suitable for operation in offshore platform because it does not require complex and additional surface facilities in the relatively limited platform life span. However, the characteristics of offshore oilfield also bring many challenges which do not exist in the onshore oilfield. For example, the large well spacing will push out the influence of polymer degradation, and the degradation effect is easy in high temperature condition [13]; the high salinity will reduce the tackability of polymer [14,15].

In previous works, many mathematical models of polymer flooding have been built [16–18]. In these models, some of the viscoelastic effects, the polymer degradation and the salt sensitivity are neglected, or poorly handled. Moreover, many commercial simulation software of polymer flooding such as CMG, ECLIPSE and UTCHEM which are widely used in oilfield also have similar problems [19–24]. As a result, it will present an inaccurate forecast of the production performance for polymer flooding. In order to reflect the mechanisms and its influences more accurately and comprehensively, first, a novel model of polymer flooding is built, which considers both the mechanisms in traditional models and the new mechanisms such as viscoelasticity, degradation and strong salt-sensitivity. Then, in order to increase the convergence, IMPES method and Runge–Kutta method are used to solve the novel model. Finally, the factors such as injection rate, polymer molecules, water salinity, degradation velocity and well spacing which affect the development effect of polymer flooding by affecting the viscoelasticity, degradation and salt-sensitivity are investigated based on Bohai Bay oilfield using the novel model.

2. Experiments of salinity sensitivity and degradation

2.1. Salinity sensitivity

Three types of polymer produced by Beijing Hengju Chemical Group Co., Ltd., China are used to carry out the experiments of salinity sensitivity. The concentration of polymer solution is

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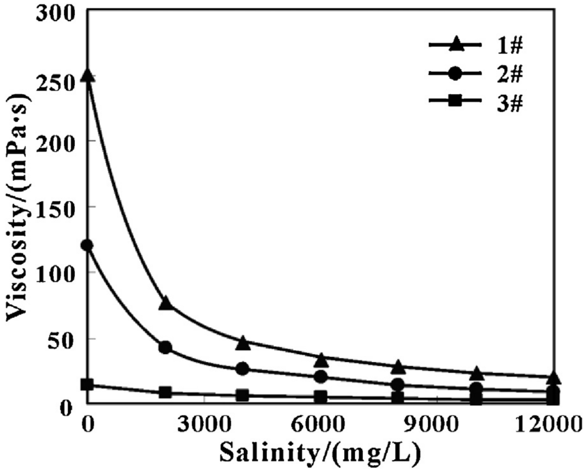

Fig. 1. Curves of salinity effect of polymer.

2000 mg/L, and the concentrations of NaCl are 0, 2000, 4000, 6000, 8000, 10,000, 12,000 mg/L, respectively. The shear viscosity of polymer solution is measured by Brookfield LVDV-II+Pro rotational viscometer (Brookfield Corporation, USA) with the shear rate of 6 rpm at 25 °C, and the result is shown in Fig. 1. It is clear that, when the salinity is lower, the shear viscosity sharply decreases as the salinity increases; when the salinity is higher, the viscosity basically keeps stable.

2.2. Degradation effect

A type of polymer with good stability which is produced by Sichuan Guanya Polymer Chemical Limited Company, China is used to carry out the degradation experiments of polymer. First, prepare 2000 mL polymer solution with the polymer concentration of 3000 mg/L and NaCl concentration of 5000 mg/L; then, divide it into two samples and put them into the thermotanks with the temperature of 40 °C and 50 °C, respectively. After the polymer dissolved completely, take out part of the polymer solution and test its viscosity by Brookfield LVDV-II+Pro rotational viscometer with a very low shear rate as the initial viscosity. Every period of time, take out part of the polymer solution and measure its viscosity. Thus, the polymer degradation curves are achieved, which is shown in Fig. 2.

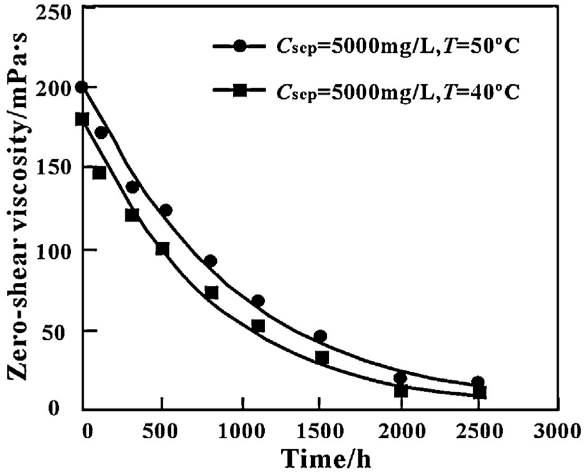

Fig. 2. Curves of polymer degradation.

3. Governing equation

3.1. Mass conservation equations

The assumptions imposed on the flow equations include local thermodynamic equilibrium, slightly compressible fluids and reservoir rocks, Fickian dispersion, ideal mixing, broad Darcy's law and all chemical species transport in the aqueous phase only. The boundary conditions are no flow and no dispersive flux across the impermeable boundaries.

According to the Darcy's law, the mass conservation equations of all the components are expressed as follows.

Mass balance equation for oil:

$$\nabla \cdot \left[\frac{\vec{K} K_{ro}}{\mu_o B_o} (\nabla p_o - \rho_o g \nabla D) \right] + Q_o = \frac{\partial}{\partial t} \left(\frac{\phi S_o}{B_o} \right) \tag{1}$$

Mass balance equation for water:

$$\nabla \cdot \left[\frac{\vec{K} K_{rw}}{\mu_{we} B_w R_k} (\nabla p_w - \rho_w g \nabla D) \right] + Q_w = \frac{\partial}{\partial t} \left(\frac{\phi S_w}{B_w} \right) \tag{2}$$

Mass balance equation for polymer:

$$\nabla \cdot \left[\frac{\vec{K} K_{rw} C_p}{\mu_{we} B_w R_k} (\nabla p_w - \rho_w g \nabla D) \right] + \nabla \cdot (\vec{d}_p \phi f_p S_w \nabla C_p) + Q_w C_p = \frac{\partial}{\partial t} \left(\frac{\phi f_p S_w C_p}{B_w} \right) + \frac{\partial [f_p (1-\phi) \rho_r \hat{C}_p]}{\partial t} \tag{3}$$

Mass balance equation for salt:

$$\nabla \cdot \left[\frac{\vec{K} K_{rw} C_s}{\mu_{we} B_w R_k} (\nabla p_w - \rho_w g \nabla D) \right] + \nabla \cdot (\vec{d}_s \phi S_w \nabla C_s) + Q_w C_s = \frac{\partial}{\partial t} \left(\frac{\phi S_w C_s}{B_w} \right) + \frac{\partial [(1-\phi) \rho_r \hat{C}_s]}{\partial t} \tag{4}$$

In which, B_l is the volume factor of phase l, m^3/m^3; C_i is the concentration of component i, kg/m^3; $\hat{C}_i$ is the adsorbed concentration of component i, kg/kg; D is the vertical depth, m; d_i is the diffusion coefficient of component i, m^2/s; f_p is the effective pore volume factor; $\vec{K}$ is the intrinsic permeability tensor, μm^2; K_{rl} is the relative permeability of phase l; p_l is the pressure of phase l, Pa; Q_l is the source and sink for phase l, m^3/(day m^3); R_k is the polymer permeability reduction factor; S_l is the saturation of phase l; μ_o is the viscosity of oil phase, mPa s; μ_{we} is the effective viscosity of water phase, mPa s; φ is the porosity; $\bigtriangledown$ is divergence operator; i represents component polymer or salt; l represents phase water or oil; o represents oil phase; w represents aqueous phase.

3.2. Auxiliary equation

Let S_w and S_o be water and oil saturation respectively. Then the saturation constraint equation is,

$$S_o + S_w = 1 \tag{5}$$

Also, the p_w and p_o is water and oil phase pressure respectively, the capillary pressure equation is,

$$p_{cow}(S_w) = p_o - p_w \tag{6}$$

In which, p_{cow} is the capillary pressure between o and w, Pa.

3.3. Process mechanism model of viscoelastic polymer flooding

3.3.1. Effective viscosity of polymer solution

Polymer solution is a shear-thinning fluid in rheometry. It presents three districts, as shown in Fig. 3(a), and the viscosity is