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NUMERICAL SIMULATION STUDY ON SURFACTANT FLOODING FOR LOW PERMEABILITY OILFIELD IN THE CONDITION OF THRESHOLD PRESSURE*

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Abstract: Based on the non-Darcy flow characteristics of surfactant flooding in the low permeability oilfield, considering the changes of threshold pressure and influence of surfactant on convection, diffusion, adsorption and retention, a mathematical model is established for a three-dimensional, two-phase, three-component surfactant flooding. A new treatment for the changes of threshold pressure and a novel correction method for the relative permeability curve in the process of surfactant flooding are derived, which enhances the matching degree between the mathematical model and field practice. The mathematical model was used to perform the numerical simulation study for a pilot test of surfactant flooding in Chao 45 Block of Daqing Oilfield, a proper injection plan was optimized. After the optimized plan was carried out in oilfield, the desirable effects, like pressure-reducing, injection rate increase, and the increase of oil recovery, were achieved. The average oil increase for single well reaches 37%, the ratio of cost to revenue is above 1:4, so the economic effect of scale is promising.

Key words: low permeability, surfactant, non-Darcy flow, threshold pressure gradient, numerical simulation

1. Introduction

The laboratory experiments show that the surfactant flooding can reduce oil-water interfacial tension[1], increase the dispersion of oil in water, make oil droplets more deformable and so easier to pass pore throat[2-4], lower the threshold pressure and reduce residual oil saturation[5,6]. The reflection is the moving-up and right shift of oil phase's relative permeability curve, and the increase of end-point value of water phase's relative permeability curve. The concrete phenomena in oilfield production are that the amount of water injection increases and the recovery efficiency is enhanced as the injection pressure decreases[7]. Several pilot tests of surfactant flooding were carried out in Daqing's low permeability oilfields, such as Yushulin Oilfield and Chaoyanggou Oilfield, the objectives of pilot tests are to reduce the injection pressure, to increase the injection rate and to enhance the oil recovery. Because the cost of surfactant is comparatively high, before the surfactant flooding is applied in oilfield, the reservoir numerical simulation study is first used to determine the optimal concentration of surfactant, proper amount of surfactant injected, and injection mode to obtain the maximum economic benefit.

At present, the main commercial surfactant flooding softwares are UTCHEM and GRANDTM. Both softwares do not consider a threshold pressure[8], and are primarily used for medium-high permeability reservoir[9]. For the low permeability oilfield, the most obvious strength of surfactant flooding is the reduction of threshold pressure, the increase of

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production rate and enhanced oil recovery efficiency. Therefore, the current commercial simulation software cannot simulate the above mechanisms. In this article, a new mathematical model of surfactant flooding, based on a compositional model, is established. A new treatment method for the changes of threshold pressure and a novel correction method for the relative permeability curve in the process of surfactant flooding are included in the model. This model was used to optimize the injection plan for pilot test of surfactant flooding in Chaoyanggou Oilfield of Daqing, in order to provide a theoretical support for the decision on the development of oilfield.

2. Mathematical model of surfactant flooding

Because of the threshold pressure in low permeability oilfield, the flow of oil and water are non-Darcy one[10]. When the surfactant is added into the injection water, there are three components: oil, water and surfactant in the reservoir fluids. In the meantime, the threshold pressure will decrease with the increase of concentration of surfactant. Based on the above mechanism of fluid flow in porous media, a mathematical model of surfactant flooding for low permeability oil field, which includes the anisotropy and heterogeneity of rock, the compressibility of rock and fluid, and the influences of convection, diffusion and adsorption, is established and analyzed as follows[11-13].

Continuity equation of oil component:

$$\nabla\bullet(\rho_o \boldsymbol{v}_o) = \frac{\partial}{\partial t}(\phi\rho_o s_o) - \rho_o q_o \tag{1}$$

Continuity equation of water component:

$$\nabla\bullet(\rho_w \boldsymbol{v}_w) = \frac{\partial}{\partial t}(\phi\rho_w s_w) - \rho_w q_w \tag{2}$$

Continuity equation of surfactant[14]:

$$\begin{aligned}&\nabla\bullet\phi\rho_s(D_{os}s_o\nabla C_{os} + D_{ws}s_w\nabla C_{ws}) + \\ &\nabla\bullet(\rho_s \boldsymbol{v}_o C_{os}) + \nabla\bullet(\rho_s \boldsymbol{v}_w C_{ws}) = \\ &\frac{\partial}{\partial t}(\phi\rho_s s_o C_{os} + \rho_s a_{os} + \phi\rho_s s_w C_{ws} + \\ &\rho_s a_{ws}) - \rho_s q_o C_{os} - \rho_s q_w C_{ws}\end{aligned} \tag{3}$$

$$s_o + s_w = 1 \tag{4}$$

$$M = \frac{C_{os}}{C_{ws}} \tag{5}$$

where C_{os} is the concentration of surfactant in oil phase, fraction, C_{ws} the concentration of surfactant in water phase, fraction, a_{os} the adsorption quantity of surfactant in oil phase, a_{ws} the adsorption quantity of surfactant in water phase, D_{os} the diffusion velocity of surfactant in oil phase, D_{ws} the diffusion velocity of surfactant in water phase, M phase equilibrium constant.

The non-Darcy flow equations for oil, water phases are:

$$\boldsymbol{v}_o = -\frac{KK_{ro}}{\mu_o}[\nabla p_o - \rho_o g\nabla z \pm \boldsymbol{e}G_{op}(C_{os}, s_w)] \tag{6}$$

$$\boldsymbol{v}_w = -\frac{KK_{rw}}{\mu_w}[\nabla p_w - \rho_w g\nabla z \pm \boldsymbol{e}G_{wp}(C_{ws}, s_w)] \tag{7}$$

where $\boldsymbol{e}$ is unit vector, $\boldsymbol{e} = \boldsymbol{i} + \boldsymbol{j} + \boldsymbol{k}$, $G_{op}(C_{os}, s_w)$, $G_{wp}(C_{ws}, s_w)$ are the threshold pressure gradients of oleic phase and water phase, respectively. The choice of positive or negative signs for threshold pressure is determined by the signs of $\frac{\partial p}{\partial x}$, $\frac{\partial p}{\partial y}$ and $\frac{\partial p}{\partial z}$, and the signs between them are always opposite to guarantee that the threshold pressure gradient is always the resistance force. If

$$\left|\frac{\partial p_o}{\partial x}\right| - G_{op}(C_{os}, s_w) \le 0$$

then $v_{ox} = 0$. The treatment of fluid velocity in other directions are similar.

3. Treatment of threshold pressure gradient

When crude oil flows in the low permeability reservoir, the reasons that cause the threshold pressure are the ultimate shear stress[15], namely the yield value, exists as crude oil flows in the porous media. The