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Full Length Article

A systematic numerical modeling study of various polymer injection conditions on immiscible and miscible viscous fingering and oil recovery in a five-spot setup

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ABSTRACT

Polymer flooding is employed to prevent immiscible viscous fingering between oil and water. If the polymer injection concentration is decreased rapidly, there is a high chance that fast growing miscible viscous fingers will pierce through the polymer bank and enter the oil bank. This is very detrimental to oil production. We performed numerical modeling of polymer flooding in one-quarter of a five-spot system. Due to the nonuniform flow field in a five-spot setup, the fingering patterns are very different and miscible fingers are more detrimental in this case than in a rectangular domain. In this paper we quantify the impact of injection concentration and duration of polymer flooding on the growth rate of miscible and immiscible viscous fingers. Besides decrease and increase of immiscible and miscible viscous finger growth at the front and rear of polymer banks respectively, we have shown that the residual oil saturation decreases for higher injection concentrations. However for high injection concentrations, polymer should be injected for a long duration so that the width of the polymer bank is large and miscible fingers cannot cause short-circuiting. Since injection at constant concentration for a long duration is not optimal, simulations for different multi-step injection were performed. Our results demonstrate that arbitrary decreases in polymer injection concentration are not effective for enhancing oil recovery. The ideal polymer injection scheme suggested by our simulations should involve an initial constant rate, followed by a gradual decrease. This is mainly to overcome the retardation due to adsorption of the polymer.

1. Introduction

Polymer flooding is widely used in oil industry to enhance oil recovery. In this method, a water soluble polymer is added with water to increase its viscosity. It improves the ability of water to push the oil through the porous medium as a result of more favourable mobility ratio preventing the immiscible viscous instability [14]. The increase of sweeping efficiency by polymer flooding depends on the geometry, well configuration and flow field. Most of the previous studies on polymer flooding were conducted in rectangular domain. Those studies were useful for a horizontal well systems. But for common oil recovery systems, the wells are vertical. In case of a five-spot configuration, one production well is at the center and four injection wells are at the corners of a square. Unlike the rectangular geometry, five-spot geometry exhibits point singularities at the sink and/or source and have a contact interface that expands radially as the flow evolves. This results in stronger velocity gradients [12]. A quarter of five-spot system is sufficient to study viscous instabilities in five-spot system because of the flow symmetry. Emami Meybodi et al. [6] used five spot glass model to conduct experiments to understand the effect of heterogeneity on polymer flooding. They demonstrated the applicability of micro model for polymer enhanced oil recovery method in both locally and globally heterogeneous five-spot models. Al-Sofi et al. [1] investigated the effect of shear thinning behaviour of polymer on oil recovery efficiency in five-spot system. They found that shear thinning of polymer did not affect oil recovery in homogeneous reservoir but reduced the cumulative oil production in heterogeneous reservoirs. Hematpour et al. [10] carried out experiments to understand the behaviour of polymer flooding in a low viscosity oil field by using a one-quarter five-spot glass micro model. They studied the effects of several parameters such as polymer types, polymer concentration, injection rate, pore structure and connate water on ultimate oil recovery of polymer flooding. Falode and Afolabi [7] performed numerical simulations of polymer flooding in five-spot injection well to study the effects of clay minerals on polymer flooding performance. They demonstrated the importance of clay minerals in adsorption of polymer which may reduce the displacement efficiency of the polymer flooding process. Sedaghat et al. [22] studied the effects of salinity and connate water saturation on

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recovery efficiency of polymer flooding for both oil and water wet reservoirs in five-spot pattern. They used the numerical simulators, UTCHEM, to predict the flow behaviour of polymer flooding in fractured model. They found good agreement between the numerical results and their experimental results.

In a typical polymer flooding process, the reservoir is often flooded first with polymer thickened water and then by water without polymer. This reduces the cost of recovery. However this may lead to miscible viscous fingering behind the polymer bank if a high value of polymer concentration is used to displace highly viscous oil. So for controlling both immiscible and miscible viscous fingering, one has to analyze the potential viscous instability at both the front and rear of the polymer bank. Past studies [11,15,16,20,32] on miscible viscous instability in rectangular domain, revealed that growth rate and wave lengths of fingers are controlled by various transport parameters. The growth rate and wave lengths of immiscible viscous fingers during two phase displacement in porous medium are controlled by the viscosity ratio, relative permeability and interfacial tension [9,21,25,30]. There are very less number of studies on viscous fingering phenomena (either immiscible or miscible) for a quarter five-spot system.

Most of the previous studies for radial or one-quarter five-spot flow problems dealt with miscible viscous instabilities in porous media [2,12,13,17–19,31]. Zhang et al. [31] studied the miscible viscous fingering in one-quarter five-spot geometry both experimentally and numerically. They showed good comparison between the numerical results and experimental results of miscible viscous finger evolution for different mobility ratios. Chen and Meiburg [2] demonstrated the effect of mobility ratio and flow rate on miscible viscous fingering for homogeneous porous media. Petitjeans et al. [18] conducted experiments and numerical simulations of miscible viscous fingering in a quarter of five-spot geometry in Hele-Shaw cell. They studied the effect of flow rate, Peclet number and viscosity contrast on the sweep efficiency of the miscible displacement. Riaz and Meiburg [19] used a vorticity based approach to model the miscible viscous fingering in a three dimensional heterogeneous porous media for a quarter five-spot geometry. They studied the effect of density driven gravity override on miscible displacement in porous media for both homogeneous and heterogeneous permeability fields. They observed that gravity override was suppressed in the heterogeneous case. Islam and Azaiez [12] studied the thermal effect on the miscible viscous fingering. They found that the fluid front became more unstable due to faster diffusion of thermal front. This effect was more significant in case of radial flow than rectilinear flow because of the strong velocity gradient in a radial flow field. Nicolaides et al. [17] investigated the impact of viscosity contrast and permeability heterogeneity on mixing in porous media in a quarter five-spot system.

A few authors studied the immiscible viscous fingering and finger evolution with time in a quarter of five-spot system [5,24,29]. Sheorey and Muralidhar [24] investigated the influence of hot water injection on the immiscible viscous fingering between oil and water. They showed more recovery when hot water was injected. Yadali Jamaloei et al. [29] conducted experiments to study low tension polymer flooding. They found the number of micro-fingers increases with square root of time. Djebouri et al. [5] studied the effect of permeability ratio of two layers on the growth of immiscible viscous fingers during water flooding in a quarter five-spot system. They observed higher growth rate of immiscible viscous fingers near high permeable zones.

It is clear from the literature survey on viscous instabilities in radial and five-spot system, that no previous studies discussed the simultaneous growth of immiscible and miscible viscous fingers during polymer flooding. Recently Vishnudas and Chaudhuri [26] showed the importance of studying the simultaneous growth of immiscible and miscible fingers during polymer flooding in rectangular domain. They showed that for higher concentrations of polymer, miscible fingers can spear through the polymer bank and create a short-circuit. The growth of the immiscible and miscible fingers are very sensitive to various transport parameters [27]. In a five-spot system, the growth of immiscible and miscible fingers are expected to be more complex due to diverging and converging flow field. Hence a comprehensive study on various types of viscous instabilities during polymer flooding in this geometry is necessary. In this paper we have presented numerical simulation results for polymer flooding in a one-quarter of five-spot system, for different polymer injection concentrations and durations. Two major contributions in this paper are as follows:

(i) The simultaneous growths of immiscible and miscible viscous instabilities in five-spot setup during polymer flooding have been demonstrated for the first time in this paper. The evolutions pattern of immiscible and miscible viscous fingers and the interactions among themselves for different mobility ratios (due to varying polymer injection concentration) have been discussed in detail. We have highlighted the major differences between the evolution of fingers in five-spot and rectangular domain. (ii) The second contribution is in regards to finding the optimum mass of injected polymer for higher oil recovery. Several numerical simulations for different polymer injection concentrations and durations were performed for achieving the optimum polymer injection strategy. The cumulative oil recovery and cumulative amount of injected polymer have been compared for different injection conditions. We have shown how miscible viscous fingering behind the polymer bank can be more detrimental to oil recovery in five-spot system when polymer injection concentration is decreased rapidly after a short duration of polymer flooding. Later a few simulations were performed for gradual decrease of polymer injection concentration in multiple steps. The effect of step size, starting time and rate of decrease concentration on oil recovery are demonstrated and discussed.

2. Mathematical modelling

We consider two-phase flow in a porous medium where both fluids are immiscible. Isothermal multiphase fluid flow in a oil reservoir is governed by the conservation of mass and momentum. The mass conservation equation for each fluid phase (α) and generalized Darcy equation representing momentum balance can be mathematically written as,

$$\frac{\partial}{\partial t}(\rho_\alpha \phi S_\alpha) + \nabla.(\rho_\alpha \mathbf{q}_\alpha) = 0 \quad \text{and} \quad \mathbf{q}_\alpha = -\frac{k k_{r\alpha}}{\mu_\alpha}\nabla(p_\alpha + \rho_\alpha g z). \tag{1}$$

where S_α, $\mathbf{q}_\alpha$, p_α, $k_{r\alpha}$, μ_α and ρ_α are respectively the saturation, seepage flux, pressure, relative permeability, viscosity and density for phase α. We consider water to be wetting fluid ($\alpha = w$) and oil to be non-wetting fluid ($\alpha = nw$). So for water and oil, α takes 'w' and 'nw' respectively. Here ϕ and k respectively denote the porosity and intrinsic permeability of the porous medium. The sum of the oil and water saturations must be equal to one i.e, $S_w + S_{nw} = 1$ for two phase flow.

The expressions for relative permeability are often given in terms of the normalized water saturation (S_e), defined as $S_e = \frac{S_w - S_{rw}}{1 - S_{rw}}$, where S_{rw} is the residual saturation of wetting phase fluid i.e. water here. The Brooks-Corey relationship between wetting and non-wetting phase relative permeabilities (k_{rw} and k_{rnw}) with wetting phase saturations (S_w) can be written as follows

$$k_{rw} = S_e^{e_w} \tag{2}$$

$$k_{rnw} = (1 - S_e)^{e_{nw}}, \tag{3}$$

Where as e_w and e_{nw} are relative permeability exponents of water and oil respectively. The values of the constants are given in Table 1. The Brooks-Corey capillary pressure (p_c) - water saturation (S_w) relationship below was used:

$$p_c = p_{nw} - p_w = C_{pc}\sqrt{\frac{\phi}{k}}\,(1 - S_e)^{e_{pc}}, \tag{4}$$

The values of capillary pressure constant (C_{pc}) and capillary exponent (e_{pc}) are given in Table 1.