Fuel 194 (2017) 480–490

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

A comprehensive numerical study of immiscible and miscible viscous fingers during chemical enhanced oil recovery

R. Vishnudas, Abhijit Chaudhuri *

Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai 600 036, India

HIGHLIGHTS

- Explored all possible immiscible and miscible instabilities during polymer flooding.
- Viscous fingers are characterized by Fourier analysis and growth rate vs time curves.
- Fingers merging, tip splitting and the trailing lobe detachment are captured well.
- All results by UTCHEM are consistent with previous knowledge from analytical studies.
- Miscible fingers can grow very fast and puncture the polymer bank to invade oil bank.

ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form 1 December 2016
Accepted 5 January 2017
Available online 18 January 2017

Keywords:
Miscible
Immiscible viscous fingering
Chemical enhanced oil recovery
Polymer flooding
Amplitude spectra

ABSTRACT

Miscible and immiscible viscous fingering in porous media are undesirable for many engineering applications such as chemical enhanced oil recovery, contaminant transport, and liquid chromatography. For chemical enhanced oil recovery, polymer is injected to prevent immiscible viscous fingering between aqueous and oil phases. Polymer solution weakens the growth of immiscible viscous fingers but it may actuate miscible viscous fingering behind the polymer bank when polymer flooding is followed by water flooding. Due to the adsorption of polymer and presence of connate water, two saturation shocks are most commonly formed during polymer flooding. Therefore during typical polymer flooding two immiscible viscous fingering can occur around two saturation shocks. We have performed a Fourier analysis of the saturation and polymer concentration contours at water-oil interface and concentration front after the onset of viscous fingering to obtain the amplitude spectra for different instabilities. We also have calculated root mean square (RMS) of fingers and its variation with time. The Fourier analysis and calculation of RMS at different times are very useful to quantify the evolution of growth rate spectrum for immiscible and miscible instabilities. We have shown that due to adsorption the width of polymer bank decrease very fast for low injection concentration. In this case polymer bank disappear and polymer flooding becomes ineffective. But for high injection concentration the miscible viscous fingers grow very fast and reach the oil bank. This can affect the efficiency of oil displacement.

1. Introduction

The displacement of immiscible fluids and transport of the solute in porous media are greatly affected by viscous fingering when the viscosity increases in the direction of flow. The immiscible viscous instability, which is due to viscosity difference between two fluids, is a subject of considerable interest in the fields of reservoir engineering, enhanced oil recovery (EOR), ground water hydrology, irrigation and infiltration [8,11]. The dependence of viscosity on the solute concentration leads to miscible viscous instability. The stability of miscible displacement processes in porous media is of special interest in the areas of enhanced oil recovery, liquid chromatography, contaminant transport, etc. [23,33]. A typical injection pattern in polymer enhanced oil recovery process involves injection of polymer solution (polymer-thickened-water) that is followed by water injection. It is very attractive for tertiary oil recovery, because only relatively minor modifications are needed to water flooding to enable polymer injection. It helps to increase the ultimate oil recovery [20,24,34]. Recently, Zhou et al. [42] concluded that for heavy oil reservoirs, polymer flooding is an effective enhanced oil recovery method.

Many previous analytical and semi-analytical studies [5–7,15,29,35,39,40] have discussed the formation of saturation

* Corresponding author.
E-mail address: abhijitiisc@gmail.com (A. Chaudhuri).

http://dx.doi.org/10.1016/j.fuel.2017.01.014
0016-2361/

shock and immiscible viscous fingering of two phase flow in porous media. The Buckley-Leverett fractional flow formulation has proven to be very useful for predicting the saturation shock height and velocity. The Buckley-Leverett saturation profile is the solution of immiscible displacement process if the effects of capillary pressure and gravity are neglected [40]. The presence of capillary pressure does not affect the shock speed, but it smears the saturation profile around the saturation front [28]. Based on normal mode analysis, Yortsos and Huang [40] showed that mobility ratio was the governing condition for an immiscible viscous instability. They also carried out asymptotic analysis to derive a parabolic dependence of growth rate on wave numbers. Chikhliwala et al. [5] confirmed the same by numerical solution of linear stability analysis for both capillary and non-capillary effects in a rectangular geometry. Riaz and Tchelepi [27] showed the impact of relative permeability functions on instability for a wide range of relative permeability vs saturation profiles. Their results showed that a two phase flow system was more prone to instability for the relative permeability profiles corresponding to the drainage process than imbibitions process. Riaz and Tchelepi [29] developed a numerical framework to perform accurate numerical solution of growth rate of fingers and compared with linear stability analysis for different mobility ratios. Most recently, Wijeratne and Halvorsen [38] numerically investigated viscous fingering in a heavy oil reservoir with water drive. Thus the immiscible instability for two-phase flow in porous medium was very well studied and these understandings are useful for control of instability during water flooding. But during the polymer flooding the immiscible instability at saturation shock between oil and polymer solution is more complex because the mobility ratio and shape of saturation shock depend on the transport properties of polymer. Miscible viscous fingering was studied by several authors [1,4,10,18,22,25,26,33,41,44] for different solutes, which can change the viscosity of the solution. Based on linear stability analysis, Tan and Homsy [33] derived the expression of growth rate of miscible viscous fingers for a rectilinear displacement in porous medium. They found that solute dispersion reduces the growth rate of miscible viscous fingers.

Since both immiscible and miscible viscous fingering can affect fluid displacement, a combined analysis of both instabilities and finger growth rates are very important for chemical enhanced oil recovery (CEOR). Wang and Dong [37] carried out polymer flooding experiments in sand pack to obtain the relation between the effective viscosity of the polymer solution and the tertiary oil recovery efficiency. They showed that an optimum range of effective viscosity can be found for the injected polymer solution. Daripa and Pasa [9] analytically derived an optimum viscosity profile of polymer solution to control viscous fingering within a HeleShaw cell. However there are no previous quantitative studies of the simultaneous growth of miscible and immiscible viscous fingers in porous media during polymer flooding. During the propagation of polymer solutions in reservoirs, some amount of polymer may adsorb into the solid surface. This leads to a considerable drop of aqueous phase polymer concentration. So the outcome of the polymer flooding is expected to differ if the adsorption of polymer is taken into account. A nonlinear Langmuir isotherm is suitable for modeling the equilibrium adsorption [13,19]. However such nonlinear adsorption imparts substantial complexity to the modeling of miscible and immiscible viscous instability. Hence there is a need to solve multiphase flow and nonlinear transport equations to determine the growth rates for simultaneous occurrence of miscible and immiscible viscous instabilities. It is impossible to analytically solve these non-linear system of equations and predict the growth rate of immiscible and miscible viscous fingers. But it is very important to understand the behavior of these viscous fingers to arrive an optimum polymer injection conditions. In this paper we numerically simulated miscible and immiscible viscous fingering during polymer flooding followed by water drive using UTCHEM. We compared the saturation shock speed and height with the fractional flow method. We explored all possible viscous instabilities during typical polymer flooding chemical enhanced oil recovery processes. The dynamic evolution of the viscous fingers were captured by Fourier analysis of the saturation or concentration contour and rate of change of root meen square (RMS) of saturation/concentration contours. The effects of injection concentration on the comparative growth of immiscible and miscible fingers were also studied.

2. Mathematical modeling

The governing equation for modeling two phase flow in porous medium is given as,

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

where $S_\alpha, \mathbf{q}_\alpha, p_\alpha, k_{r\alpha}, \mu_\alpha$ and ρ_α are respectively the saturation, seepage flux, pressure, relative permeability, viscosity and density for phase α. Here ϕ and k respectively denote the porosity and the intrinsic permeability of the porous medium. The values of the constants are given in Table 1. In this study water and oil are respectively considered as wetting phase and non-wetting fluids. So subscript 'w' and 'nw' are used to represent water and oil phases. The following relations are used to express wetting and non-wetting phase relative permeabilities (k_{rw} and k_{rnw}) as the functions of wetting phase saturations (S_w).

$$k_{rw}(S_w) = S_e^{e_w} \quad \text{and} \quad k_{rnw}(S_w) = (1 - S_e)^{e_{nw}}, \tag{2}$$

where S_e is effective saturation of wetting phase and it is defined as $S_e = \frac{S_w - S_{rw}}{1 - S_{rw}}$. The residual saturation of wetting phase fluid is denoted as S_{rw}. The values of the exponents e_w and e_{nw} are given in Table 1. To model the imbibition (i.e. injection of water or wetting phase fluid) during water flooding into oil reservoir, we considered Brooks-Corey capillary pressure-saturation relationship, which is given as,

$$p_c = p_{nw} - p_w = C_{pc}\sqrt{\frac{\phi}{k}}(1 - S_e)^{e_{pc}}, \tag{3}$$

where p_c is capillary pressure. The wetting and non-wetting phase pressure are denoted as p_w and p_{nw}. The values of capillary pressure

Table 1
Reservoir and fluid properties.

Property	Value
porosity (ϕ)	0.22
permeability (k)	2500 mD
water relative permeability exponent (e_w)	3.6
oil relative permeability exponents (e_n)	2.5
residual water saturation (s_{wc})	0.1
residual oil saturation	0
water viscosity (μ_w)	1 cp
oil viscosity (μ_0)	500 cp
capillary constant (C_{pc})	10 mN/m
capillary exponent (e_{pc})	3
water density (ρ_w)	1 g/cm^3
oil density (ρ_o)	0.75 g/cm^3
longitudinal dispersion coefficient (α_L)	0.3 m
transverse dispersion coefficient (α_T)	0.01 m
A_{p1}	12.54 (wt%)$^{-1}$
A_{p2}	41 (wt%)$^{-2}$
A_{p3}	715 (wt%)$^{-3}$
A	6.5
B	100