



Analytical solutions of oil displacement by a polymer slug with varying salinity



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ABSTRACT

This paper presents an analytical solution of a non-self-similar, two-phase, multi-component problem of polymer slug injection with varying water salinity (ionic strength) in oil reservoirs. The non-Newtonian properties of polymers are incorporated into the fractional flow, yielding the velocity dependency of the fractional-flow function. Using the Lagrangian coordinate instead of time allows splitting the initial system ($n+1 \times n+1$) into a $n \times n$ system for concentrations and one scalar hyperbolic equation for phase saturation, which allows for full integration of the non-self-similar problem of wave interactions. The solution includes implicit formulae for saturation, polymer, and salt concentrations and front trajectories of the components. The solution allows determining the slug size of the low-salinity water that prevents the contact between the polymer and the high-salinity water.

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1. Introduction

Polymer flooding aims at improving sweep efficiency of the water displacement process by increasing the mobility ratio between the displacing agent and the in-situ oil. This is achieved by adding a polymer to the aqueous phase. The rheology of the polymer solution depends on parameters such as polymer concentration, velocity, and salt concentration. For example, if polymer concentration is held constant, the viscosity of a polymer solution increases as salt concentration decreases. This means that for given oil viscosity target, potentially less polymer would be required to maintain mobility control as salinity decreases (Sorbie, 1991). Furthermore, it has been observed that more oil is released from rocks when the salinity of the aqueous phase is reduced. This is mainly attributed to modifications in the wetting state of the rock surface among other mechanisms (Lager et al., 2008; Mahani et al., 2015). This implies that the combined effect of low-salinity water and polymer can in principle be utilized to improve oil recovery in economically and operationally favourable conditions. To minimize the cost of low-salinity polymer (LSP) injection, usually a slug (fraction of the reservoir pore volume) of polymer is injected and then followed by one or more slugs with reduced polymer concentration and, finally, by a water drive.

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Effects of the polymer and of lowering the salinity can be modelled through modifying the fractional-flow functions: addition of polymer increases viscosity of the displacing agent, and lowering the salinity affects the relative permeability parameters (Mohammadi and Gary, 2012). Analytical methods are useful in understanding the underlying physics of many enhanced oil recovery processes (Pope, 1980; Bedrikovetsky, 1993; Lake, 1989). These methods can also be used to check the accuracy of the numerical schemes that are employed for large-scale simulations. Multiple discontinuities in the solutions of multi-component slug injections typically create major difficulties in numerical modelling, whereas the analytical solutions provide trajectories for the multiple shocks and the parameter jumps across the trajectories. Moreover, one-dimensional analytical models form the basis for streamline and front-track simulators of three-dimensional flows in heterogeneous formations (Ewing, 1983; Holden and Risebro, 2002).

Continuous injection of a fluid having a constant composition into a reservoir initially saturated by another fluid with a constant composition corresponds to so-called Riemann problems, with initial conditions corresponding to the reservoir fluid saturation and composition, and boundary conditions of the injected fluid fractional flow and composition. The Riemann solutions are self-similar (Gel'fand, 1959; Courant and Friedrichs, 1976), and depend on the group $\xi = x/t$. The solutions contain individual discontinuities of each component, and can exhibit chromatographic separation of the components. Numerous

Nomenclature

a	concentration of adsorbed polymer
c	polymer concentration in water (g/m ³)
c_s	salt concentration in water (g/m ³)
c_s^D	salt concentration in the drive (g/m ³)
D	shock speed for (x, t) co-ordinates
f	water fractional flow
H	power law coefficient (Pa s ^{n})
K	absolute permeability (m ²)
k_r	relative permeability of liquid phase
L	reservoir size (m)
n	power-law exponential index
p	pressure (Pa)
S	water saturation
t	time
RF	recovery factor
u	total velocity (m/s)
u_w	aqueous phase velocity (m/s)
V	shock speed in (x, φ) co-ordinate
V_p	polymer slug volume per unit area (m ³ /m ²)
x	coordinate

Greek letters

Γ	Henry's polymer sorption coefficient
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η	self-similar coordinate φ/x
κ	Bulk power law coefficient (Pa s ^{n})
μ	apparent viscosity (Pa s)
ϕ	porosity of porous media
ξ	self-similar coordinate x/t
φ	potential function

Subscripts

H	high salinity water
L	low salinity water
o	oil
s	salt
w	water

Superscripts

D	drive condition
I	initial condition
J	injection condition
$+$	value ahead of the shock
$-$	value behind the shock
$*$	intermediate point

authors have provided solutions for one- and multi-component, two-phase flow systems that allow for different kinds of dependencies of parameters (De Nevers, 1964; Claridge and Bondor, 1974; Helfferich, 1981; Hirasaki, 1981; Braginskaya and Entov, 1980).

Johansen and Winther (1988) and Johansen et al. (1989) solved the Riemann problem for a multi-component, two-phase system by projecting it onto the solution of a single-phase problem. The authors prove that the direct projection transforms all elementary waves of two-phase system into those for a single-phase system. So, the solution process consists of finding a solution for one-phase flow and extending it to two-phase flow. The projection principle allows for algorithmic integration of an arbitrary Riemann problem for two-phase multi-component with adsorption, based on the corresponding solute transport problem for a single-phase flow. However, the projection is valid for Riemann problems only: the two-phase flow solution with non-constant initial or boundary conditions cannot be mapped onto the corresponding one-phase-flow solution.

Injection of multi-component slugs corresponds to non-self-similar solutions. The qualitative phase plane with characteristics is presented in (Fayers, 1962) for sequential displacement of oil by intercalated slugs of cold and hot water. The exact integration is achieved by decomposition of the problem with piece-wise-constant initial and boundary conditions into local Riemann problems and solution of interactions of the elementary waves (Bedrikovetsky, 1982, 1993). Integration of the conservation law over the invariant contours yields the exact solutions with explicit formulae for trajectories of curvilinear fronts and for saturation and concentration distributions. In the simplified case, where adsorption of a component is a function of its own concentration only, the exact integration shows that the multi-component slugs interact after the injection and finally separate into single-component slugs moving in order of decreasing the sorption derivative values, similar to Rhee et al. (1998) for one-phase flows. Nevertheless, for the general case, where the adsorbed concentrations

depend on the concentrations of all components, the analytical solution is not available in the literature.

Pires et al. (2006) and Borazjani et al. (2016) show that the introduction of Lagrangian coordinate φ (stream function) associated with mass conservation for water in n -component two-phase flow problems and using it as an independent variable instead of time t allows separating the $(n+1) \times (n+1)$ hyperbolic system into an $n \times n$ auxiliary one-phase system and one scalar equation (so called lifting) for two-phase flow. The auxiliary system and the lifting equation are the results of transformation of conservation laws for water and for all components, respectively, in co-ordinates (x, φ) . In various cases, where the auxiliary system allows for an analytical solution, the general system is reduced to the solution of a single scalar equation (Pires et al., 2006). In contrast to direct projection onto the one-phase solution that is valid for Riemann problems only (Johansen and Winther, 1988; Johansen et al., 1989), this mapping results in splitting for any initial and boundary-value problems.

Generally, the solution of the lifting equation is obtained numerically (Vicente et al., 2014). However, for the case of linear adsorption isotherms, even with the Henry's constants depending on other concentrations, the lifting problem allows for exact solution (Borazjani et al., 2014).

In this paper the splitting method presented by Pires et al. (2006) is applied for hyperbolic systems corresponding to two-phase multi-component flows in the reservoir scale approximation. Yet, recently the splitting method has been extended for two-phase multicomponent systems of parabolic PDEs accounting for capillary pressure and non-equilibrium phase transitions and chemical reactions (Borazjani et al., 2016).

The objective of this work is to provide exact solutions based on the mapping presented in Pires et al. (2006) for the cases when the displacing aqueous phase contains varying viscosity and salinity. Our special focus is to describe the physics of the process when a slug of low-salinity polymer is followed by injection of polymer-free aqueous solutions. The adsorption of the chemical

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