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Research paper

A chemical EOR benchmark study of different reservoir simulators

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ABSTRACT

Interest in chemical EOR processes has intensified in recent years due to the advancements in chemical formulations and injection techniques. Injecting Polymer (P), surfactant/polymer (SP), and alkaline/surfactant/polymer (ASP) are techniques for improving sweep and displacement efficiencies with the aim of improving oil production in both secondary and tertiary floods. There has been great interest in chemical flooding recently for different challenging situations. These include high temperature reservoirs, formations with extreme salinity and hardness, naturally fractured carbonates, and sandstone reservoirs with heavy and viscous crude oils.

More oil reservoirs are reaching maturity where secondary polymer floods and tertiary surfactant methods have become increasingly important. This significance has added to the industry's interest in using reservoir simulators as tools for reservoir evaluation and management to minimize costs and increase the process efficiency. Reservoir simulators with special features are needed to represent coupled chemical and physical processes present in chemical EOR processes. The simulators need to be first validated against well controlled lab and pilot scale experiments to reliably predict the full field implementations.

The available data from laboratory scale include 1) phase behavior and rheological data; and 2) results of secondary and tertiary coreflood experiments for P, SP, and ASP floods under reservoir conditions, i.e. chemical retentions, pressure drop, and oil recovery. Data collected from corefloods are used as benchmark tests comparing numerical reservoir simulators with chemical EOR modeling capabilities such as STARS of CMG, ECLIPSE-100 of Schlumberger, REVEAL of Petroleum Experts. The research UTCHEM simulator from The University of Texas at Austin is also included since it has been the benchmark for chemical flooding simulation for over 25 years.

The results of this benchmark comparison will be utilized to improve chemical design for field-scale studies using commercial simulators. The benchmark tests illustrate the potential of commercial simulators for chemical flooding projects and provide a comprehensive table of strengths and limitations of each simulator for a given chemical EOR process. Mechanistic simulations of chemical EOR processes will provide predictive capability and can aid in optimization of the field injection projects. The objective of this paper is not to compare the computational efficiency and solution algorithms; it only focuses on the process modeling comparison.

1. Introduction

Conventional recovery from oil reservoirs based on natural depletion by energy of fluid (reservoir depressurization) is referred to as primary production. After pressure decline, reservoir pressure must be increased by injecting water or gas as a secondary recovery to achieve higher oil production. Furthermore, it is recognized that water flooding cannot mobilize viscous oils or droplets of original oil trapped in smaller pores due to capillary force especially in fractured carbonate reservoirs. Injected water will flow through fractures easily and residual oil will remain unswept in smaller pores. There can be further oil recovery after the secondary recovery by decreasing oil viscosity using thermal methods for heavy oil reservoirs. Furthermore, other methods are changing the wettability of the fluids with respect to the rock or decreasing interfacial tension (IFT) between water and oil by chemicals added to the injection water such as surfactant or alkaline. These methods are referred to as Enhanced Oil Recovery (EOR) processes (Lake, 1989; Green and Willhite, 1998). In recent years chemical processes are considered as valuable EOR methods for mature depleted light oil conventional reservoirs, non-thermal recovery of viscous oils, and fractured carbonate reservoirs using chemicals for wettability alteration (Delshad et al., 2006; Darabi et al., 2012).

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Nomenclature

A	flow area (m^2)
A_{p1}, A_{p2}, A_{p3}	matching parameters for UTCHEM polymer viscosity model
a_{41}, a_{42}, b_4	polymer adsorption parameters in UTCHEM
a_1, a_2, b	polymer adsorption parameters in ECLIPSE
$AD(C, T)$	adsorption isotherm of polymer in CMG-STARS
$ADMAXT$	maximum adsorption capacity of the rock in CMG-STARS
B_w	water formation volume factor
b_{rk} , c_{rk}	permeability reduction parameters in UTCHEM
C	polymer concentration in ECLIPSE
ca	mole fraction of polymer in aqueous phase for CMG-STARS
C_P	polymer concentration in ECLIPSE
C_{13}	water concentration in ME phase (volume fraction)
C_{23}	oil concentration in ME phase (volume fraction)
C_{33}	surfactant concentration in ME phase (volume fraction)
$C_{4\ell}$	polymer concentration in phase l (wt%)
C_5	total anions concentration in UTCHEM (meq/ml)
C_6	divalent cations in UTCHEM (meq/ml)
C_p^{α}	polymer adsorption in phase α for ECLIPSE
$C_p^{\alpha\ \max}$	maximum polymer adsorption in phase α for ECLIPSE
C_{SE}	salinity in ECLIPSE (molality)
C_{SEP}	parameter for salinity effect on polymer viscosity
E, F	empirical parameters for surfactant phase behavior in UTCHEM
F_w	water flow rate in ECLIPSE (m^3/day)
$f(x_a)$	mixing function for polymer viscosity in CMG-STARS
K	grid block permeability (md)
K_{ref}	reference permeability (md)
m	exponent for concentration dependency of polymer viscosity in ECLIPSE
M	viscosity thickening or thinning multiplier in ECLIPSE
n	exponent for permeability dependency in ECLIPSE
P	viscosity thickening or thinning multiplier in ECLIPSE
$R_{k\ \max}$	permeability reduction for polymer in UTCHEM
RRF	residual resistance factor in ECLIPSE
R_{23}	oil solubilization ratio (dimensionless)
S_l	liquid saturation (fraction)
S_p	parameter for divalent cation effect on polymer viscosity
$tad1$, $tad2$, $tad3$	polymer adsorption matching parameters in CMG-STARS
x_a	component mole fraction (fraction)
$xnacl$	salinity in CMG-STARS (mass fraction)
μ_w	water viscosity (cp)
μ_a	component viscosity (cp)
$\mu_m(C_p)$	ME viscosity (cp)
μ_{ME}	ME viscosity (cp)
μ_p	polymer viscosity at maximum polymer concentration (cp)
μ_{sh}	shear polymer viscosity in ECLIPSE
$\dot{\gamma}_c$	shear rate coefficient in CMG-STARS
$\dot{\gamma}_{eq}$	equivalent shear rate in UTCHEM and CMG-STARS
σ_{23}	oil/ME interfacial tension (mN/m)
σ_{ow}	water/Oil interfacial tension (mN/m)
α_1, α_2, α_3, α_4, α_5	matching parameters for ME viscosity in UTCHEM
ϕ	porosity (fraction)
ω	Todd–Longstaff mixing parameter for polymer viscosity in ECLIPSE

Chemical EOR methods have been studied extensively in the lab and field tested for several decades. Its application has been encouraging and is now more visible. Because of great advances in recent years, many of the original issues and limitations hindering the application of chemical EOR no longer exist.

Different commercial reservoir simulators can be used for modeling these complex chemical EOR processes. In this paper, the performance of VIP and REVEAL for chemical processes will be discussed briefly, but the main focus will be on CMG-STARS, ECLIPSE, and UTCHEM due to their worldwide applications. The laboratory coreflood experiments are modeled and compared in CMG-STARS and UTCHEM. Pandey et al. (2008) used CMG-STARS extensively to model coreflood experiments for better understanding of flow mechanisms during chemical flood and also to generate parameters which will be used subsequently in field scale simulations. Morel et al. (2008) used the ECLIPSE polymer module to perform a feasibility study of polymer injection in the Dalia field, and their studies demonstrated useful results about injectivity and additional oil recovery.

Reveal (Petroleum Experts, 2012) is a full field reservoir simulator from Petroleum Experts with the capability for modeling surfactant phase behavior and also mobility control, which includes both polymer and gel options. The surfactant module is similar to that in UTCHEM and can define different phase behaviors (Type I, Type II, and Type III) based on salinities. Reveal has the capability of modeling polymer and several polymer-gel kinetics based on shear thinning behavior near wellbore. Reveal has options for permeability reduction, inaccessible pore volume, gelation of polymer and a cross-linker, and degradation. It also includes a foam model for increasing gas phase viscosity especially in heavy oil reservoirs.

VIP (Landmark, 2012), Landmark's reservoir simulation suite, has the capability for thermal simulation of hot water and steam injection as well as polymer flooding in the black oil model.

In this paper, we compare chemical models of UTCHEM, CMG-STARS, and ECLIPSE for polymer, Surfactant/polymer, and alkaline/surfactant/polymer floods. A brief description of the capability of these simulators is presented here.

1.1. UTCHEM

UTCHEM is a three dimensional multiphase multicomponent chemical compositional simulator, which is capable of simulating different chemical EOR processes (Satoh, 1984; Saad, 1989; Bhuyan, 1989; Aldejain, 1989; Delshad, 1994; Goudarzi et al., 2012, 2015; Korrani et al., 2015; Lashgari et al., 2015, 2016). The simulator can account for complex phase behavior and chemical reactions. The simulator can generate up to four phases (gas, aqueous, oleic, and microemulsion) and uses advanced concepts in high-order numerical accuracy and dispersion control. Microemulsion (ME) is a combination of water, oil, surfactant, and co-surfactant that at certain conditions of temperature, pressure, and salinity can form a single separate phase, which is thermodynamically stable. It has the modeling capabilities for wettability alteration, capillary pressures, up to four-phase relative permeabilities as a function of trapping number, full tensor dispersion, molecular diffusion, adsorption, chemical reactions arising during high pH alkaline flooding, non-equilibrium mass transfer between phases, and other related phenomena.