Journal of Petroleum Science and Engineering 131 (2015) 96–113

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Modeling of capacitance flow behavior in EOS compositional simulation

Bo Zhang, Ryosuke Okuno*

School of Mining and Petroleum Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2W2

ARTICLE INFO

Article history:
Received 2 October 2014
Accepted 10 April 2015
Available online 22 April 2015

Keywords:
Gas injection
Fluid characterization
Equations of state
Bypassed oil recovery
Compositional flow simulation

ABSTRACT

Gas injection is a widely used method for enhanced oil recovery. Oil bypassing by gas occurs at different scales because of micro and macroscopic heterogeneities, gravity segregation, and front instability. Part of the bypassed oil can be recovered by crossflow between the bypassed and flowing regions. This characteristic of reservoir flow is referred to as capacitance flow behavior in the literature. Modeling of such flow behavior at the sub-grid scale is challenging in the conventional flow simulation since fluids are perfectly mixed and in equilibrium within individual grid blocks under the local equilibrium assumption.

This research investigates capacitance flow behavior in compositional reservoir simulation. An efficient two-step method is presented to model bypassed oil recovery in multiphase compositional flow simulation of gas floods. The oil bypassing is first quantified by use of the dual-porosity flow with two dimensionless groups; bypassed fraction and throughput ratio. To represent bypassed oil recovery in single-porosity flow, a new flow-based fluid characterization is applied to part of the heavy fractions of the fluid model used. Properties for pseudo components can be determined based on the throughput ratio estimated in the dual-porosity flow. Case studies for various reservoir/fluid properties show that single-porosity flow with the new method reasonably represents bypassed oil recovery observed in core floods and fine-scale heterogeneous simulations.

1. Introduction

Gas injection is a widely used method for enhanced oil recovery. The interplay of fluid flow with phase behavior can yield multicontact miscibility between reservoir oil and injection gas (Johns, 1992; Dindoruk, 1992; Orr, 2007). Therefore, design of gas injection processes often requires compositional simulation that can accurately model properties of equilibrium phases by use of a cubic equation of state (EOS) (Coats, 1980; Watts, 1986; Collins et al., 1992). Compositional simulation attempts to consider various complexities that exist in actual reservoir processes by increasing the generalization level of the conservation equations. (Chang et al., 1990; Cao, 2002). Fundamental assumptions always made include the local equilibrium assumption, where fluids are perfectly mixed and in equilibrium within individual continua (i.e., grid blocks) (Lake, 1989).

The continuum assumption is made to calculate large-scale fluid flow in porous media with a finite-difference scheme, in which grid blocks are greater than a representative elementary volume (REV) (Lake, 1989; Hill, 1963). The local discontinuities of an actual porous medium are not taken into account under the continuum assumption. The grid-block scales in a practical finite-difference reservoir simulation are much greater than the REV (Salehi et al., 2013). Fluid properties in a grid block at each time step are then calculated with the local equilibrium assumption, where the thermodynamic equilibrium is calculated for a given set of overall composition, pressure, and temperature.

Oil bypassing by gas occurs at different scales because of micro and macroscopic heterogeneities, gravity segregation, and front instability. It has been observed in various types of experiments and field applications of gas injection. Flow-visualization experiments (Stalkup, 1970; Chatzis et al., 1983; Campbell and Orr, 1985; Bahralolom et al., 1988; Stern, 1991) showed that microscopic oil bypassing was related to pore structures with bimodal or wide pore-size distributions. Shielding of oil by water films in pores can also hinder the contact between the bypassed oil and injection gas in the region with high water saturations (Shelton and Schneider, 1975; Spence et al., 1980; Wylie and Mohanty, 1997; Wylie and Mohanty, 1999). These results clearly indicate that oil bypassing is present even at the microscopic scale smaller than a REV.

At macroscopic scales greater than a REV, gas channeling creates slow-flow or stagnant regions in heterogeneous reservoirs (Cinar et al., 2006; Al-Wahaibi et al., 2007). Thin shales with a thickness of only a

* Correspondence to: 3-114 Markin/CNRL, Natural Resources Engineering Facility, University of Alberta, Edmonton, Alberta, Canada T6G 2W2. Tel.: +1 780 492 6121.
E-mail address: rokuno@ualberta.ca (R. Okuno).

http://dx.doi.org/10.1016/j.petrol.2015.04.014
0920-4105/

Nomenclature

Roman Symbols

A	Area
A_m	Dimensionless attraction parameter for mixtures
a_i	Attraction parameter for component i in a cubic equation of state
B	Bypassed fraction
b_i	Covolume parameter for component i in a cubic equation of state
c_{Dh}	Dimensionless volume-shift parameter of introduced pseudo heavy components
c_{hi}	Volume-shift parameter of component hi
e	Coefficient defined for permeability correlation
f	Exponent defined for permeability correlation
K	Permeability
$\vec{n}$	Outward unit normal vector
n_c	Number of components
n_p	Number of phases
P_C	Critical pressure
$\vec{q}^{\,T}_{ij}$	Molar flux vector of component i in phase j from the flowing fraction to the bypassed fraction
R_T	Throughput ratio
S	Surface area
S_C	Surface area of coarse-scale grid block
S_j	Saturation of phase j
t	Time
t_D	Dimensionless time
T_C	Critical temperature
$\vec{U}_j$	Flow velocity of phase j
V	Volume
V_C	Volume of coarse-scale grid block
x_{ij}	Mole fraction of component i in phase j
x_D	Dimensionless distance
z_i	Overall mole fraction of component i

Abbreviations

DPF	Dual-porosity flow
EOS	Equation of state
MMP	Minimum miscibility pressure
PC	Pseudo component
PR	Peng-Robinson
PVI	Pore-volume injected
SPF	Single-porosity flow

Greek symbols

φ	Porosity
ρ_j	Molar density of phase j
γ_a	Attraction-parameter index
γ_h	Molar-ratio index

Subscripts/superscripts

B	Bypassed fraction
D	Dimensionless
F	Flowing fraction
hi	Introduced heavier oil component i
i	Component i
j	Phase j
m	Mixture
oi	Original oil component i
T	Transverse direction

few inches can cause marked oil bypassing by gas (McGuire et al., 1995). Front instability can also lead to oil bypassing, if the mobility ratio between the injection gas and reservoir oil is large (Gardner and Ypma, 1984; Brock and Orr, 1991).

Part of bypassed oil can be recovered by the transverse mass flux between the bypassed and flowing regions as reported by a number of researchers (Pande, 1992; Pande and Orr, 1994a, 1994b; Burger et al., 1994, 1996; Burger and Mohanty, 1997; Zhou et al., 1997; Cinar et al., 2006; Al-Wahaibi et al., 2007). The transverse flux between the two regions can occur because of diffusion, dispersion, viscous forces, and capillarity [Pande, 1992; Pande and Orr, 1994a, 1994b]. Gradual migration of oil from the bypassed region to the flowing region can cause the resulting composition profile to deviate from the one without the transverse mass flux (Brock and Orr, 1991; Pande and Orr, 1994a; 1994b; Zhou et al., 1997). High residual oil saturations were observed in dominant flow paths due to the interaction of phase behavior with oil bypassing (Gardner and Ypma, 1984; Campbell and Orr, 1985; Bahralolom et al., 1988; Mohanty and Johnson, 1993). These results indicate the importance of considering the effects of oil bypassing on oil recovery.

The degree of miscibility between oil and gas also affects the level of bypassing in gas floods (Mohanty and Johnson, 1993; Burger and Mohanty, 1997). Experimental results (Burger et al., 1994) showed that the bypassed-oil fraction was smaller for less miscible processes. It was stated that the optimum gas enrichment can be below the minimum miscibility enrichment for a secondary gas flood with a high-viscosity ratio, where the sweep and local displacement efficiencies take a balance. In the mechanistic investigation of bypassed-oil recovery in CO_2 injection (Khosravi et al., 2014), a maximum recovery was achieved at sub-miscible conditions, where the oil swelling and vaporization enhanced the recovery of bypassed oil significantly. Also, it is not always economical or technically feasible to inject a gas that is miscible with oil (Bardon et al., 1994; Al-Wahaibi et al., 2007; Ren et al., 2011). In this research, the focus is on gas floods at sub-miscible (or immiscible) conditions.

The key characteristic of reservoir flow with oil bypassing is that the oil held in the bypassed (slow-flow or stagnant) region is gradually migrated to the flowing region through the transverse mass flux between the bypassed and flowing regions. This flow behavior has been referred to as capacitance. The capacitance flow behavior observed in core floods has been studied by use of mathematical models since late 1950s. The capacitance flow was observed as earlier breakthrough of the displacing component and longer tailing of the effluent-concentration history for the displaced component (Coats and Smith, 1964; Barker, 1977). The convection-dispersion model (Aronofsky and Heller, 1957) was confirmed to be incapable of reproducing the asymmetrical effluent-concentration histories of core-flood experiments (Coats and Smith, 1964; Barker, 1977; Zhang, 2014).

Deans (1963) proposed a capacitance model for single-phase flow, in which the pore volume was divided into the flowing and bypassed fractions. The longitudinal convection occurred only in the flowing fraction. Effective mass transfer coefficients were used to model the local transverse mass flux between the two regions. Coats and Smith (1964) included the longitudinal dispersion for the flow fraction on the basis of the capacitance model of Deans