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Injectivity errors in simulation of foam EOR

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ABSTRACT

Injectivity is a key factor in the economics of foam enhanced oil recovery (EOR) processes. Poor injectivity of low-mobility foam slows the production of oil and allows more time for gravity segregation of injected gas. The conventional Peaceman equation (1978), when applied in a large grid block, makes two substantial errors in estimating foam injectivity: it ignores the rapidly changing saturations around the wellbore and the effect of non-Newtonian mobility of foam. When foam is injected in alternating slugs of gas and liquid ("SAG" injection), the rapid increase in injectivity from changing saturation near the well is an important and unique advantage of foam injection. Foam is also shear-thinning in many cases. This paper considers the two problems in turn: non-Newtonian effects and foam dry-out.

In studying non-Newtonian effects we use the method-of-characteristics approach of Rossen et al. (2011), which resolves both changing saturations and non-Newtonian rheology with great precision near the wellbore, and compare to conventionally computed injectivity using the Peaceman equation in a grid block. By itself, the strongly non-Newtonian rheology of the "low-quality" foam regime makes a significant difference to injectivity of foam. However, one could estimate this effect using the equation for injectivity of power-law fluids, i.e. without accounting for changing water saturation near the well, without much error.

In SAG processes, however, non-Newtonian rheology is less important than accounting for foam collapse in the immediate near-wellbore region. Averaging water saturation in a large grid block misses this dry-out very near the well and the Peaceman equation grossly underestimates the injectivity of gas. This error is similar in kind to, but much greater than, that in conventional gas-injection EOR. The magnitude of the effect on the overall simulation decreases as the simulation grid is refined around the well; this grid refinement is especially important for simulating foam SAG processes. We illustrate with examples using foam parameters fit to laboratory data.

1. Introduction

Enhanced Oil Recovery (EOR) processes employing gas injection (miscible and immiscible solvent or steam injection) can be very efficient in recovering oil where the gas sweeps. Unfortunately, gas injection has poor sweep efficiency (Lake et al., 2014) because of geological heterogeneity, density differences between gas and oil or water, and viscous instability between the gas and the oil or water it displaces. Foam can address all three causes of poor sweep efficiency (Schramm, 1994; Kovscek and Radke, 1994; Rossen, 1996).

The economics of any EOR process depends on maintaining sufficient injectivity. Injectivity is especially problematic in foam EOR (see e.g., Namdar Zanganeh and Rossen, 2013). Simply injecting a very-low-mobility fluid can force a reduction in injection rate to avoid fracturing the injection well. Unintended fracturing of the injection well has plagued some foam applications in the field (Kuehne et al., 1990; Martinsen and Vassenden, 1999). Moreover, injection rate is crucial to the ability of foam to overcome gravity override of injected gas (Rossen et al., 2010). The good injectivity of a SAG process, in which gas and surfactant solution are injected as alternating slugs, is a major advantage for this injection method in overcoming gravity override (Shan and Rossen, 2004; Faisal et al., 2009; Kloet et al., 2009; Boeije and Rossen, in press). In principle, the best foam process for overcoming gravity override in a homogeneous reservoir is a SAG process with one large slug of surfactant solution followed by one large slug of gas.

Two issues complicate the correct prediction of injectivity in SAG foam EOR processes in reservoir simulation, and in particular injectivity of the gas slug. The first is the reaction of foam to changing water saturation close to the well. Foam dries out and collapses abruptly as water saturation falls below a certain value S_w^* (Khatib et al., 1988; Rossen and Zhou, 1995; Alvarez et al., 2001). This "dry-out effect" means that the mobility of gas increases enormously near the injection well and this greatly increases injectivity. Second, gas in

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Nomenclature

H	reservoir height [m]
k	reservoir permeability [darcy]
k_{rg}^{f}	gas relative permeability [dimensionless]
k_{rw}	water relative permeability [dimensionless]
epdry	STARS foam parameter [dimensionless]
φ	reservoir porosity [dimensionless]
fmmob	reference mobility reduction factor [dimensionless]
FM	foam mobility factor [dimensionless]
S_o	oil saturation [dimensionless]
S_w	water saturation [dimensionless]
S_{wc}	connate water saturation [dimensionless]
S_{wr}	irreducible water saturation [dimensionless]
S_g	gas saturation [dimensionless]
f	fractional flow [dimensionless]
f_w	water fractional flow [dimensionless]
Q	injection rate [m^3/s]
t	time [s]
t_D	dimensionless time [dimensionless]
λ	mobility [m^2/(Pa s)]
λ_{rt}	total relative mobility [m^2/(Pa s)]
r	radius [m]
r_w	well radius [m]
r_e	outer radius [m]
P	pressure [Pa]
P_D	dimensionless pressure [dimensionless]
P_w	pressure at well [Pa]
P_{re}	pressure at edge of gridblock [Pa]
n	power-law exponent [dimensionless]
μ	viscosity [Pa s]
μ_g	gas viscosity [Pa s]
μ_w	water viscosity [Pa s]
x	position [m]
x_D	dimensionless position [dimensionless]
C_s	surfactant concentration [dimensionless]
MOC	method of characteristics
SAG	surfactant alternating gas
EOR	enhanced oil recovery

foam is a non-Newtonian fluid, at least in some circumstances (Hirasaki and Lawson, 1985; Falls et al., 1989; Alvarez et al., 2001; Xu and Rossen, 2003; Tang and Kovscek, 2006). Its shear-thinning properties reduce the pressure gradient near the well, which increases injectivity.

The Peaceman equation (1978) is used in most finite-different simulators to describe the difference between injection-well pressure and surrounding pressure in a grid block. It faces various challenges dealing with well placement within the grid block, wellbore orientation, permeability anisotropy, partial penetration of the grid block by the well, large aspect ratio in the dimensions of the grid block, and the effect of a hydraulic fracture (Peaceman, 1983, 1993; Babu et al., 1991; Chen et al., 1995; Mochizuki, 1995; Abacioglu et al., 2009; Dogru, 2010; Ibrahim, 2013). These challenges, and extensions of the equation to meet them, are not the focus of this study. This study addresses errors in the Peaceman equation relating specifically to foam EOR.

This paper addresses the dry-out effect in foam and non-Newtonian mobility in turn. For simplicity we focus on two-phase gas–water flow with foam, and assume that mobile oil has been displaced from the near-wellbore region.

Upon gas injection in a SAG foam process, a Buckley–Leverett shock front forms at the leading edge of the gas bank (Rossen et al., 1999; Shan and Rossen, 2004). At the shock there is an abrupt drop in water saturation and water fractional flow. Figs. A3 and A4 in Appendix A show an example. This front is followed by a two-phase spreading wave that extends back to the well, in which foam dries out and collapses. In total, two regions are present; a spreading wave with two-phase flow, and ahead of it flow of liquid only. In our study foam dries out near the well because of water displacement and flow. Evaporation of water into the gas is another mechanism of dry-out and mobility increase near the well, as examined in other studies of gas injectivity without foam (McMillan et al., 2008; Pickup et al., 2012). We do not consider evaporation here, but evaporation may also be an issue for foam.

Our focus is the near-wellbore area, so we assume that surfactant concentration is uniform and constant in the water phase as a result of earlier surfactant injection. We model injectivity during gas injection in a SAG process in two ways. First we represent the region of interest as a grid block, as in reservoir simulators (Computer Modeling Group, 2006; Schlumberger, 2010; Sharma et al., 2011). The injection pressure is calculated from the Peaceman equation (1978), assuming a cylindrical geometry for a rectangular shaped grid block and uniform properties in the grid block. Second, we use the Method of Characteristics (MOC) to examine saturation and mobility near the well and overall injectivity in the same