Immiscible N2 Injection for EOR: An Experimental Comparison Study

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Title: Immiscible Nitrogen Injection for Enhanced Oil Recovery: An Experimental Comparison Study.

Abstract:

Gas injection is a widely applied Enhanced Oil Recovery (EOR) method. The main mechanism for incremental oil recovery by this method is its lower residual oil saturation compared to water flooding (Lake, 1989; Green and Willhite, 1998; Simjoo, 2012). However, poor vertical and areal sweep efficiency result in inefficient oil displacement by gas injection. Water-Alternating-Gas (WAG) injection has been widely used for controlling gas mobility, aiming at more stable oil displacement.

It has been established that miscible gas flooding is based on the following main displacement mechanisms (Lake, 1989; Bhoendie *et al*., 2014): 1) oil swelling, 2) viscosity reduction of the oil phase and 3) reduction of the interfacial tension (IFT) between the oil and displacing phase. However, a knowledge gap exists regarding the displacement mechanisms for immiscible gas flooding methods.

The purpose of this study is to investigate how rock-fluid and fluid-fluid interactions control the immiscible gas flooding processes. To this end several well-controlled core-flood experiments were conducted using the following EOR schemes: 1) continuous nitrogen injection at varying increasing pressure, 2) continuous nitrogen injection at constant pressure of 5 bar, 3) continuous nitrogen injection at constant pressure of 10 bar, 4) water flooding followed by continuous nitrogen injection and 5) WAG injection. Nitrogen was injected into Bentheimer sandstone saturated with n-hexadecane either at connate water saturation or at residual oil saturation to water flood. X-ray CT images were taken during water and gas propagation to map the fluid saturations distributions over time and to gain insight in the displacement mechanism responsible for the enhanced oil production.

Figure 1 presents an overview of the ultimate recovery factors corresponding to the tests conducted in this study. It shows an improvement in oil recovery during WAG injection of approximately 10% of the oil initially in place (OIIP) compared to continuous gas injection. The first three cycles contributed the most to the enhanced oil recovery (Figure 2B).

The anomalously high incremental oil recovery in the WAG experiment is most likely due to an increase in trapped gas saturation. During imbibition cycles, water saturation increases as well as the trapped gas saturation, resulting in a lower gas relative permeability. Subsequently this can cause oil mobilization and a reduction of the three-phase residual oil saturation.

From this comparison study the following conclusions can be drawn:

- From the injection strategies studied, WAG resulted in the highest ultimate recovery factor (approximately 59.0 % of the OIIP).
- An increase in pressure favours oil recovery during continuous nitrogen injection at initial oil saturation.
- Continuous nitrogen injection gave rise to higher ultimate recovery factors than water flooding conducted at initial oil saturation.
- Residual oil saturation for immiscible nitrogen flooding is lower under three-phase flow conditions compared to two-phase flow (Figure 1,2A).

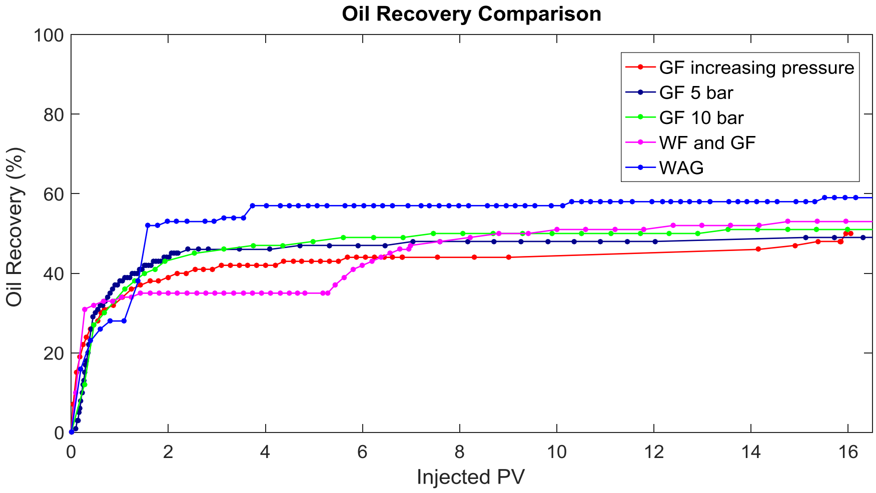

Figure 1: Oil recovery comparison between the tests conducted. GF, WF and WAG stand for gas flooding, water flooding and Water-Alternating-Gas injection respectively. Note that in test 4 water was injected and subsequently gas flooding took place. In test 5 a WAG injection scheme consisting of 12 cycles has been applied. The first three tests correspond to continuous immiscible gas flooding.

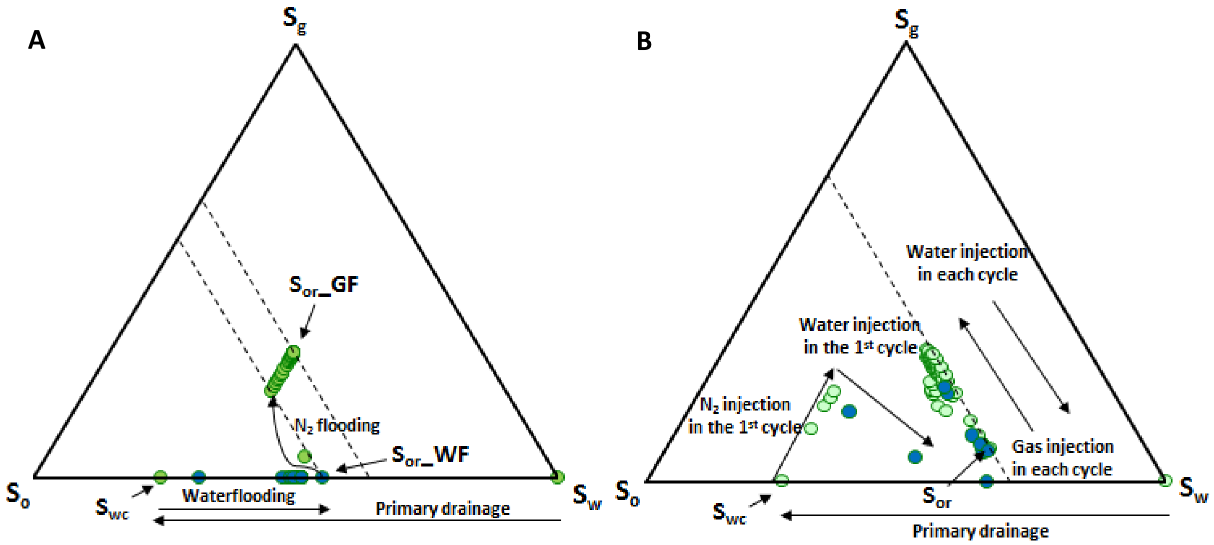

Figure 2: Schematic representation of the injection paths during A) water flooding followed by nitrogen injection and B) WAG. S_w, S_o, S_g, S_{or} and S_{wc} represent the water, oil, gas, residual oil and connate water saturations respectively. Note that the water injections are coloured blue.

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