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Experimental and numerical evaluation of the potential of improving oil recovery from shale plugs by nitrogen gas flooding

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A B S T R A C T

Production from tight formation resources leads to the growth in U.S. crude oil production. Compared with chemical flooding and water flooding, gas injection is a promising enhanced oil recovery (EOR) approach in shale reservoirs. A limited number of experimental studies concerning gas flooding in the literature have focused on unconventional plays. This paper presents experimental work for applying an immiscible N_2 flooding process in oil-saturated shale plugs. To investigate the effect of injection pressure on recovery performance, multiple core-flood tests were performed at the injection pressures of 1000 psi, 3000 psi, and 5000 psi, respectively. A lab-scale numerical simulation model was built to match the experimental data. Based on this model, we conducted sensitive studies and analyzed the recovery process.

The potential of N_2 flooding for improving oil recovery from shale core plugs has been demonstrated by the experimental observations and simulation results. Under a certain injection pressure, the results show that the oil was produced with a high and stable production rate at the initial period of the recovery process, before gas breakthrough. After that, the incremental RF decreased with the increase of a flooding period, and a much longer time had less effect on extracting more oil. We also examined the effect of injection pressure on gas breakthrough time, ultimate RF, and oil recovery history. This study illustrates that gas flooding could be considered as an improved oil recover (IOR) approach in shale oil reservoirs.

1. Introduction

Gas injection is a promising IOR method beyond the primary recovery stage. It has been developed as a mature and extensively employed IOR technique for recovering crude oil from conventional reservoirs. The injected gas phase may include hydrocarbon gas, CO_2, N_2, or a mixture of gases. The optimum selection of the gas source depends on reservoir conditions, gas availability, and economic factors. The benefits of nitrogen include its low cost, simple production process, and non-corrosive factor. It has thus become a substitute for natural gas or carbon dioxide, especially in cases where those gases are scarce.

Nitrogen injection has been demonstrated as an effective IOR/EOR approach by many published theoretical and experimental studies as well as by the successful field cases reported globally. The study history can be dated back to the 1970s. Clancy et al. (1981) summarized the potential applications of nitrogen in enhanced oil and gas recovery, which range from the simplest process of pressure maintenance to the most complex technique of miscible displacement. Ahmed et al. (1983) conducted laboratory tests for displacing crude oil using a high-pressure, N_2 injection. They determined the miscible pressure for the system and also investigated the compositional changes taking place during the displacement process. In a follow-up study, Alcocer and Menzie (1984) examined the effect of temperature and gas-oil ratio in solution on crude oil recovery and the miscibility process. Simulation studies showed a positive IOR potential: N_2 can be used effectively as an injection gas to facilitate maximized oil recovery in the fields of Trinidad (Sinanan and Budri, 2012) and the South East Asset (Belhaj et al., 2013). Heucke (2015) assessed the IOR potential of N_2 injection for oil fields in North Africa and highlighted the advantages and feasibility of such technology.

Over the past decade, U.S. crude oil production has grown rapidly, which has been primarily driven by resources from tight formations (EIA, 2015). Those areas represent low-permeability reservoirs, including shale and chalk formations. It is projected that stimulation treatments operated in the initial stage of production will become less effective with the depletion of reservoir pressure. Improved oil recovery methods must be applied to shale reservoirs to maintain and extend the production growth, in addition to the current use of horizontal wells with multiple transverse factures.

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Nomenclature

W_{dry}	weight of dry core plug sample, g	P_{in}	injection pressure, psi
W_{sat}	weight of core sample saturated with dead oil, g	P_{out}	production pressure, psi
W_{exp}	weight of core sample measured after the N_2 flooding test, g	P_{ave}	average reservoir pressure, psi
T_{exp}	designed gas injection period, day	S_g	gas saturation
φ_{gas}	porosity measured from gas porosimeter	S_o	oil saturation
φ_{sat}	porosity measured from oil saturation (weight difference)	*RF*	recovery factor
		BT	breakthrough

Researchers are considering gas injection as an IOR solution in tight formations. Gas can be injected in subsurface media continuously or cyclically, known as flooding or huff-n-puff processes. Cyclic gas injection (CGI) recovery has shown encouraging potential from blooming physical and numerical simulation studies (Song and Yang, 2013; Wan et al., 2013; Gamadi et al., 2013; Yu et al., 2014; Sheng, 2015; Yu and Sheng, 2015; Sanchez-Rivera et al., 2015; Wan et al., 2015). The action of injecting gas in the flooding mode has mainly been evaluated by reservoir modeling work. Sheng and Chen (2014) initially simulated gas and water flooding in a simple fractured shale model with the base matrix permeability of 0.1 μD. They concluded that the injection of gas greatly outperforms water. With a similar injection scheme in well-to-well flooding, Zhu et al. (2015) built a compositional reservoir model with a matrix permeability of 10 μD and 1 μD. Their results suggested there is the potential of CO_2 flooding to improve recovery in shale oil. Limited core-flood experiments have been implemented to test gas flooding IOR potential using shale core plugs. Kovscek et al. (2008) and Vega et al. (2010) tested the performance of CO_2 injection in a fractured siliceous shale core with a permeability of 0.02–1.3 mD. To the best of our knowledge, few tests have been operated under ultra-low permeability (less than 1 μD) conditions.

In this work, the oil recovery potential of N_2 flooding processes was evaluated in the Eagle Ford shale plugs with a permeability of less than 1 μD. Core-flooding tests were conducted to mainly investigate the effects of the flooding time and injection pressure on recovery performance. By performing numerical simulation on experimental tests, we have a better understanding of the gas flooding process and production history in shale reservoirs.

2. Experimental work

2.1. Materials

The core plugs used in this study were cut from the Eagle Ford shale outcrop parallel to the bedding planes with a dimension of 1.5-inch diameter and 2-inch length. The measured average helium porosity was 5% and the nitrogen permeability was about 80 nD. Permeability was determined using a complex transient measurement system (AutoLab 1000) developed by NER Inc., USA. There was no observed natural fracture or fissure inside of the plugs from CT images (Fig. 1). The oil sample used for core plug saturation was the dead shale oil with a low density of 0.815 g/cc and a viscosity of 8.5 cp under 71°F and atmospheric pressure. N_2 with a high purity of 99.999% was used as the gas source in the flooding tests.

2.2. Experimental setup

The experimental work consists of two parts: (a) core plug saturation and (b) the gas flooding process, as the setup diagram shows in Fig. 2. The apparatus used for core saturation contains a vacuum pump, a vessel, an accumulator, and a Quizix pump (QX-6000). For gas flooding tests, a core holder with a maximum operating pressure of 10,000 psi was used. Tap water, pressurized by Quizix pump, was used to supply confining pressure to the plug, which was 500 psi higher than the injection pressure. The injected gas came from a high-pressure (6000 psi) compressed N_2 cylinder. A gas mass flow meter (SmartTrak 100) with a readability of 0.02 sccm (standard cubic centimeters per minute) was installed at the outlet to monitor the gas flow rate.

2.3. Experimental procedures

In general, core samples were saturated with dead oil followed by the N_2 flooding tests. Firstly, the helium porosity of plug samples were measured by using a gas porosimeter and were calculated with Boyle's Law. An analytical balance with the readability of 0.0001 g was used to measure the plug weight when it was dry, when it was oil-saturated, and after the tests. Such high quality sensitive balance is required because the weight difference is very small when measuring plugs at various conditions.

For the saturation process, the cleaned core plugs were placed in an oven for drying 24 h with the temperature of 248°F (120 °C), and then the dried samples were placed in a vessel and vacuumed for 24 h. After that, the oil was delivered into the vessel with a constant operating pressure of 1000 psi for 24 h for maximum saturation. The relief valve was then opened and the test plug was taken out of the vessel (other plugs were put in oil before operating the flooding test). After removing the outside liquid, the plug was placed in an empty container for a few hours to equalize its pressure and stabilize the weight. The above procedure was repeated multiple times on each plug as the flooding tests were performed under different operating conditions. Comparing the results of oil-saturated weight of the plug indicated that the saturation results were almost the same. After the saturation, the flooding test could be performed by placing the test plug in the core holder with a rubber sleeve, applying confining pressure, and then injecting the gas into the plug.

2.4. Experimental design

A total of three scenarios of N_2 flooding processes were performed at different injection pressures under immiscible conditions. Scenario #1 was conducted with a constant injection pressure of 1000 psi for 5 days. Scenarios #2 and #3 were operated with a constant injection pressure of 3000 psi and 5000 psi, respectively. Since the recovery process becomes faster when higher injection pressure applied, we only monitored the recovery history of 2 days for scenarios #2 and #3, which saved the experiment operation time and allowed us to understand the recovery characters as well. To minimize the experimental errors and eliminate the impact of sample difference, the same core plug was kept for use under different scenarios. Though samples were not precisely