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Experimental and numerical study of permeability reduction caused by asphaltene precipitation and deposition during CO2 huff and puff injection in Eagle Ford shale

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ABSTRACT

The permeability reduction associated with asphaltene precipitation and deposition in gas injection EOR processes has been widely observed and well-studied in conventional plays. In our previous research, such permeability reduction due to asphaltene deposition during gas huff and puff injection process in shale core plugs were observed. In this study, experiments were conducted to investigate the permeability reduction caused by asphaltene deposition in shale core samples during the CO_2 huff and puff injection process. A dead oil sample from a Wolfcamp shale reservoir was used. A core scale simulation model was built up to mimic the huff and puff injection process in the experiment and the parameters for the asphaltene deposition in shale were obtained by matching the experimental oil recovery and permeability reduction data. The asphaltene precipitation and deposition process during the CO2 huff and puff injection experiment are discussed in details based on the simulation results.

Experimental results showed that severe permeability damage was caused by asphaltene during CO2 huff and puff injection (e.g., 48.5%), especially in the first cycle (e.g., 26.8%). Analysis of the experiments using simulation approach show that oil recovery factor reduction starts right after the beginning of CO2 huff and puff injection and the effect of asphaltene deposition on oil recovery factor accumulated during the later cycles. The asphaltene deposition was mainly formed in the near surface area of the core plug. As the CO2 concentration is quickly increased in the first cycle and more oil is near the rock surface in the first cycle, asphaltene precipitation and deposition were most significant during the huff period in the first cycle compared with the subsequent cycles. In the puff period of the first cycle, asphaltene precipitation is quickly decreased, as CO2 flow back. In addition, although oil in the inner blocks continuously flows to the outer blocks during the puff period, due to the extremely low permeability of the core plug, the amount of oil is small and this oil has already experienced the asphaltene precipitation process during the previous huff period, very small amount of increase in the asphaltene deposition occurs during the subsequent puff periods.

1. Introduction

Advanced technologies such as horizontal well and multistage fracturing have made the shale oil production practical and economical in Eagle Ford, Bakken and Marcellus. The shale oil production is projected to keep increasing in next 30 years and is expected to reach 7.08 million barrels per day by 2040 [1]. Shale oil production still suffers from sharp decline rate and low oil recovery problems. Researchers are trying to find solutions for such problems and one branch is focusing on the enhanced oil recovery (EOR) application in shales. Sheng [2] reviewed and discussed the previous experimental and simulation works on gas injection EOR in shale. In the publication, the preliminary results of EOR potentials were summarized and possibilities of different EOR methods to be applied in shale were discussed. Gas injection was believed to be more practical and efficient than other EOR method in shale, huff and puff injection is more effective than gas flooding. Because well-developed natural fractures combined with fractures created during the hydraulic fracturing may make the injected gas easily break through producers in gas flooding mode [2]. In contrast, the gas injection and oil production procedures are performed in the same well during huff and puff injection, so the injected gas will be mostly dissolved and swell the oil volume. Numerous studies on gas huff and puff injection EOR in shale have been done since then. The effects of injection pressure, soaking time, depletion rate, number of injection

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cycles, type of injection gas and other scenarios in huff and puff gas injection have been investigated experimentally and numerically [3–15]. A comparative experimental study of gas injection in shale plug by N_2 flooding and huff-n-puff injection performed by showed that the oil recovery factor obtained by the N_2 huff and puff process was approximately 11% higher than that from the N_2 flooding process [16]. The potential of gas huff and puff injection to enhance oil recovery in shale has been proved.

Our previous experimental work showed severe permeability damage caused by the asphaltene deposition during CO2 huff and puff injection in Eagle Ford shale core plugs [17]. Although gas injection induced asphaltene deposition problems in conventional reservoirs have been widely reported and well-studied, asphaltene related formation damage in shale reservoirs is seldom discussed. Previous investigations regarding asphaltene associated formation damage were mainly focusing on the gas flooding process in conventional rocks. It was generally agreed that the composition, pressure and temperature change can influence the stability of asphaltenes in oil, which could lead to asphaltene precipitating [18–22]. In gas huff and puff injection process, the composition, pressure change in the near wellbore area are much more complex than in the gas flooding process. As the same well is used for both injection and production, pressure increase and decrease occur in the same near the wellbore area during the huff period and puff period, respectively. Along with the pressure change, injection gas concentration in oil will also change, which is believed to be one of the most important factors during the asphaltene precipitation process [23–27]. For the huff and puff injection, several cycles are usually deigned to achieve higher oil recovery factor. Thus, the repeated pressure and composition change in the near wellbore area makes the asphaltene precipitation and deposition even more complex. The asphaltene precipitating and deposition during huff and puff gas injection have never been studied in the literature. Due to the fact that CO2 huff and puff injection is believed to have the most potential to be applied in shale, it is necessary to understand the asphaltene precipitation deposition process and its effects on permeability reduction and oil production loss because it was believed that a minor improvement in oil recovery, for example 1% could lead to 1.6–9 billion barrels of additional shale oil production [28,29].

In this work, CO2 huff and puff injection experiments were conducted on Eagle Ford outcrop core plugs saturated with Wolfcamp shale crude oil sample. The oil recovery factor and permeability reduction were measured during the CO2 huff and puff injection after different cycles. Core scale simulation model was built up using Winprop and GEM simulator in CMG software to mimic the CO2 huff and puff injection. Asphaltene precipitation and deposition process were also simulated using the built-in asphaltene precipitation and deposition models in Winprop and GEM simulators. The core scale simulation model was tuned and adjusted to match the experimental oil recovery data and permeability reduction data. Parameters for asphaltene precipitation model and asphaltene deposition model in shale during the CO2 huff and puff injection process were obtained which will be used for future simulation work. The asphaltene precipitation and deposition process during the CO2 huff and puff injection experiment are discussed in details based on simulation results.

2. Experimental section

2.1. Materials

A dead oil sample from a Wolfcamp shale oil reservoir was used in this study. The properties of the oil sample is shown in Table 1 and the oil composition reported in our colleague's previous publication is shown in Table 2 [7,8].

The total asphaltene content of the shale oil sample was measured and it was 0.15% using n-pentane following the modified IP143 method [30,31]. Industrial grade CO2 gas cylinder with water content less than 10 ppm (0.001%) from Airgas Company was used in this study. The core samples used in this study is Eagle Ford outcrop. Two core samples with similar permeability were selected from one batch of purchased core samples to keep the consistency. The properties of the two selected Eagle Ford outcrop core plugs are shown in Table 3. The permeability of the two core plugs were tested by Autolab-1000 system using a Wolfcamp shale oil sample at 15 MPa confining pressure and 10 MPa pore pressure. The porosity of the two core plugs were calculated from the total weight of saturated crude oil sample inside the core plugs.

Table 1
Properties of Wolfcamp dead oil.

Density at 69 °F	Viscosity at 69 °F	API Gravity
0.794 g/cm^3	3.66 cP	46.7° API

Table 2
Mole percent data of Wolfcamp dead oil [7,8].

Components	mol. Fraction	Components	mol. Fraction	Components	mol. Fraction
C3H8	0.01%	FC9	8.34%	FC21-22	2.27%
IC4	0.00%	FC10	8.34%	FC23-24	1.04%
NC4	0.01%	FC11-12	11.79%	FC25-26	1.73%
IC5	1.35%	FC13-14	9.41%	FC27-28	1.05%
NC5	1.35%	FC15-16	6.79%	FC29-30	0.50%
FC6	4.59%	FC17-18	4.94%	FC31-36	0.95%
FC7	10.68%	FC19	2.15%	FC37-40	0.94%
FC8	12.30%	FC20	1.28%	FC41 +	8.21%

2.2. Experimental apparatus

The experimental works include asphaltene precipitation measurement, shale core saturation, and CO2 huff and puff injection. The experimental setups used in this work were designed and modified based on previous studies [3,5,7–10,17,31–33]. The schematic of asphaltene precipitation measurement is shown in Fig. 1. It mainly consists of a reservoir cylinder, a filter cylinder, a filtrate cylinder, a back pressure regulator and a syringe pump. Nanomembranes were deposited in the filter cylinder supported by stainless steel frames and O-ring gasket. The oil and gas mixture in reservoir cylinder was flowed through the membranes at a constant pressure difference controlled by the back pressure regulator. During this process, the precipitated asphaltene got deposited on the membranes and the collected asphaltene precipitation on the membranes was measured following modified IP143 method [30].

The schematic of the shale core saturation setup used in this work is shown in Fig. 2. This setup mainly consists of a pressure vessel, an accumulator, a vacuum pump, pressure gauges and Quizix QX6000 pump. The schematic of the huff and puff setup used for CO_2 huff and puff injection experiment is shown in Fig. 3. This setup mainly consists of a syringe pump, a pressure vessel and pressure gauges. Prior to the CO_2 huff and puff injection, the core plug was put into the huff and puff vessel. Then CO_2 gas was flowed through the huff and puff vessel at low pressure to displace air in the vessel. After that, CO_2 gas was compressed into the huff and puff vessel using the syringe pump until the pressure in the huff and puff vessel reached the designed huff pressure. After the huff process was finished, all valves were closed and the

Table 3
Properties of tested core samples.

Core No.	Diameter, mm	Length, mm	Porosity,%	Permeability, nD
#1	38.0	50.8	9.66	38.0 ± 2.9
#2	38.1	50.6	9.47	39.0 ± 0.5