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Influence of produced natural gas on CO_2-crude oil systems and the cyclic CO_2 injection process

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ABSTRACT

In cyclic CO_2 injection practice, CO_2 has always been recycled to improve CO_2 utilization and reduce cost. To study the influence of produced natural gas on CO_2-crude oil systems and the cyclic CO_2 injection process, the extraction efficiency and solubility of a mixture of CO_2 and natural gas were investigated by extraction and solubility experiments. Interfacial tension (IFT) was measured by using the axisymmetric drop shape analysis technique, and cyclic injection experiments were conducted to study the performance of gas injection with various compositions. The results showed that both the CO_2 extraction capability and solubility in the crude oil can be reduced when adding the produced natural gas in the CO_2 stream. The reduction of extraction efficiency and solubility increases with increasing pressure. The interfacial tension (IFT) between crude oil and CO_2 linearly decreases with increasing pressure over two distinct ranges. The IFT generally increases as more natural gas is added to CO_2. In the low pressure range, the interfacial tension increase is caused by the reduced solubility of CO_2, while in the high pressure range, the weakened extraction efficiency of CO_2 is responsible for the increase. Increased interfacial tension results in a rise of 71.1% of the minimum miscibility pressure and an increase of 92.4% of the first contact miscibility pressure. Recovery of the cyclic CO_2 injection in the coreflooding is, therefore, lowered by 6.2% in the immiscible case and by 10.7% in the miscible case. The higher the injection pressure is, the more the recovery will be decreased.

1. Introduction

CO_2 injection into an oil reservoir could improve the oil recovery performance and permanently store CO_2 in the subsurface to mitigate the greenhouse gas effect (Bachu et al., 2004; Ren et al., 2016; Zhang et al., 2011). Cyclic CO_2 injection, which is also referred to as the CO_2 huff-and-puff process, is an effective EOR process in both light and heavy oil reservoirs (Thomas and Monger-McClure, 1990). This process follows three steps in each cycle: (1) CO_2 is injected into the reservoir through an injection well; (2) the well is shut to allow CO_2 to dissolve into crude oil; and (3) the well is then reopened and put back into production. Substantial work has been done to investigate the performance of the cyclic CO_2 injection process and the mechanisms involved in it. The mechanisms of cyclic CO_2 injection include crude oil expansion; crude oil viscosity reduction, as well as a reduction of the IFT between crude oil and CO_2, lighter components of crude oil extraction, and relative permeability of water and gas reduction (Bybee, 2007; Iraji et al., 2015; Menzie and Nielsen, 1963; Ren et al., 2015; Torabi and Asghari, 2007).

Monger and Coma noted that the soaking time has little influence on the performance of the cyclic CO_2 injection process after water flooding, and Haskin and Alston drew a similar conclusion in an immiscible cyclic CO_2 injection (Haskin and Alston, 1989; Monger and Coma, 1988). However, Simpson noted that in a bottom water-drive reservoir, the incremental oil recovery of the cyclic CO_2 injection process can be enhanced by increasing the soaking time (Simpson, 1988).

In immiscible cyclic CO_2 injection scenarios, the oil recovery factor is quite low and substantially increases with increased pressure when the pressure is below the minimum miscibility pressure (MMP). MMP is the lowest pressure at which the gas flooding changes from immiscible (multiple phase flow) to miscible (single phase flow) flooding (Fazlali et al., 2013; Shokrollahi et al., 2013). When the injection pressure is higher than MMP, the oil recovery factor is not sensitive to the pressure (Abedini and Torabi,

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2014; Ren et al., 2011; Shyeh-Yung, 1991). The injected CO_2 volume also plays an important role in the cyclic CO_2 injection process. Cumulative oil recovery can be improved by injecting more CO_2 (Palmer et al., 1986; Simpson, 1988).

Apart from the above operational parameters, the reservoir petrophysical properties also largely influence the performance of cyclic CO_2 injection. For example, in shale oil reservoirs, heterogeneity leads to a faster decline of the recovery rate at the production stage of the cyclic CO_2 injection process, and the oil recovery factor is primarily determined by heterogeneity. The production rate decreases with an increasing number of huff-and-puff cycles, resulting from the depleted reservoir pressure and hydrocarbon content (Chen et al., 2014).

One main feature of the above cyclic CO_2 injection process is that CO_2 has always been recycled to reduce cost and increase the CO_2 utilization efficiency. Consequently, CO_2 might be mixed with produced natural gas, and the performance of the cyclic CO_2 injection process may be affected. As mentioned above, previous studies mainly focus on the mechanisms and influencing factors of the cyclic pure CO_2 injection process. The influence of produced natural gas on the cyclic mixed CO_2 injection process has rarely been studied, which is the main objective of this work. This paper conducts extraction and solubility experiments, IFT experiments as well as cyclic gas injection experiments to study the influence of natural gas on the cyclic CO_2 injection process.

2. Experimental section

2.1. Experimental materials

Crude oil and the natural gas samples were collected from the Tarim Oilfield, China. They were the same materials as those used by Ding (Ding et al., 2015). The crude oil density at standard conditions (20 °C and 0.1 MPa) was 0.86 mg/mL, and the viscosity was 4.2 mPa s at 90 °C and atmospheric pressure. The CO_2 had a purity of 99.99%. The gas mixture was acquired by mixing CO_2 and natural gas with a volume ratio of 1:1. Tables 1 and 2 list the compositions of the crude oil, natural gas and gas mixture.

2.2. Extraction efficiency measurement

The experiment apparatus shown in Fig. 1 was used to study the extraction efficiency of the gas mixture. The apparatus mainly consists of a high pressure and high temperature cell, a high-pressure vessel, a temperature controller, a backpressure regulator and an oil gas separator. A certain volume of crude oil was pumped into the cell, and the air above the crude oil in the cell was pumped out to eliminate the influence of air on the experimental results. Then, the cell containing crude oil was heated. After an experimental temperature of 108 °C was achieved, the gas mixture was injected into the cell until both the desired gas volume and experimental pressure were achieved. After that, the cell was rotated constantly to accelerate the extraction process. During the extraction process, the pressure was monitored by the pressure gauge. When the reading of the pressure gauge became stable, indicating that the equilibrium state was achieved, the pressure gauge reading was determined as the equilibrium pressure. The back pressure was then set to be the equilibrium pressure and the gas in the cell was discharged with the measurement of the extracted hydrocarbon volume. The extraction efficiency (EE) was calculated by dividing the total volume of extracted hydrocarbon with the original crude oil volume.

2.3. Solubility measurement

The influence of produced natural gas on CO_2 solubility was studied with the same experimental apparatus shown in Fig. 1 under a temperature of 108 °C. To minimize the effect of extraction, the gas volume above crude oil was lower and was set to 10 mL in the experiments. The experimental procedure was similar to that of the extraction experiment before the equilibrium state. When the system achieved equilibrium, the gas above the crude oil was discharged first. Then, the crude oil saturated with gas was discharged. Gas solubility was determined by the ratio of the produced gas volume to the produced oil volume.

2.4. Interfacial tension measurement

The IFT between crude oil and three types of gas was determined by the axisymmetric drop shape analysis technique for the pendant drop case (Cheng et al., 1990). Fig. 2 illustrates the schematic diagram of the experimental device.

The IFT was measured by the following procedure:

First, toluene was pumped into the device to thoroughly clean the device, and nitrogen was then injected into the device to displace toluene. After toluene was driven out by nitrogen, the IFT cell was vacuumed and heated to the experimental temperature of 108 °C. Then, gas was injected into the IFT cell until the desired pressure was achieved. Afterward, a drop of crude oil was injected into the cell. When the system reached the equilibrium state, the camera photographed the oil drop. The IFT was calculated by analysing the oil drop shape.

2.5. Cyclic injection experiments

Fig. 3 shows the experiment apparatus used to conduct the cyclic injection experiments. The cyclic injection experiments were conducted at 19 MPa (immiscible condition for CO_2) and 25 MPa (miscible condition for CO_2). At each pressure, CO_2, natural gas as well as the gas mixture were used as solvents. The experimental parameters are listed in Table 3. The experimental temperature was 108 °C. Gas was injected into the core sample at a constant pressure

Table 1
Composition of the crude oil.

Component	Mass fraction (%)	Component	Mass fraction (%)	Component	Mass fraction (%)
C5	0.11	C15	4.52	C25	0.88
C6	1.6	C16	3.26	C26	0.73
C7	7.41	C17	2.87	C27	0.63
C8	10.91	C18	2.23	C28	0.54
C9	11.65	C19	2.57	C29	0.54
C10	11.66	C20	2.03	C30	0.34
C11	10.56	C21	1.63	C31	0.34
C12	7.26	C22	1.45	C32	0.3
C13	5.92	C23	1.23	C33	0.29
C14	5.56	C24	0.98	Total	100