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Oil recovery from a CO_2 injection in heterogeneous reservoirs: The influence of permeability heterogeneity, CO_2-oil miscibility and injection pattern

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ABSTRACT

This paper focuses on CO_2 injections in heterogeneous reservoirs and provides an investigation of the effects of reservoir heterogeneity, CO_2-oil miscibility, and injection patterns on oil recovery from an experimental perspective. The results show that CO_2 consumption in heterogeneous cores is generally larger than that in homogeneous cores due to the existence of a low-oil-production stage under heterogeneous conditions. Oil recovery is very sensitive to heterogeneity in a permeability contrast (PC) range of 1.0–15.5, so even weak heterogeneity can lead to a large decrease of recovery for both immiscible and miscible flooding. As to the miscibility effects, oil recovery with multi-contact miscible (MCM) CO_2 injections is higher than that of immiscible (IM) injections by 8.6%–14.1%, but it is difficult for MCM to reach a recovery as high as 90%, which is found in homogeneous cores. This phenomenon is different from some reported results from visual models, but in accordance with field tests characteristics. The injection pattern shows that the water alternating gas style (WAG) is more suitable for IM CO_2 flooding than a soaking operation. For MCM injections, it is the opposite, and the soaking process leads to higher recovery than using WAG. However, the viscosity of the residual oil markedly rises after MCM soaking, which would increase the difficulty of future enhanced oil recovery (EOR) procedures.

1. Introduction

As the most traditional source of non-renewable energy, petroleum has become increasingly important for industries. Currently, we are facing many challenges, including the declining rate of newly discovered reserves, approaching end of the useful lives of existing oil fields, extremely low oil recoveries of only approximately 30%–40%, and ultralow permeability or "tight" nature of most of the newly discovered oil fields. With the aim of increasing oil production and extending oil field life, EOR is a technique that has been adopted to remove oil from reservoirs after conventional recovery processes. Among the existing EOR methods, CO_2 injection has been proven to be very effective. From indoor research, CO_2 miscible flooding can lead to nearly 100% of the original oil in place (OOIP) under homogeneous conditions and it generates 10%–20% recovery after water flooding in field applications (Enick et al., 2012). The main mechanisms of CO_2 injection are recognized to be oil swelling, oil viscosity reduction, high miscibility capacity, and extraction of light components from oil (Holm and Josendal, 1974; Holm, 1976). Moreover, CO_2 injection also achieves underground sequestration of greenhouse gas and carbon resource utilization, contributing to inhibition of the greenhouse effect.

Permeability heterogeneity is an inherent property of reservoirs, and an absolutely homogeneous reservoir does not exist. The existing high permeability layers, artificial or natural fractures, can make all reservoirs heterogeneous to some extent. Reservoir heterogeneity has been viewed as a severe problem for performing CO_2 injection, and heterogeneity is exactly what the oil recovery of CO_2 injection is sensitive to. Many field applications in the USA, as well as field tests in the Daqing, Shengli, and Jilin oil fields in China, have proved the unfavorable influence of heterogeneity on CO_2 injection (Gao et al., 2014; Cheng et al., 2008; Peng, 2013), including: 1) the early breakthrough of CO_2, 2) great drop in oil well production (e.g., single well production decreases from 3.9t/d to 1.6t/d in the Shengli oil fields and from 6.6t/d to 1.2t/d in the Daqing

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oil fields owing to gas channeling induced by heterogeneity), 3) great increase of the gas-oil ratio and production cost, and 4) lower oil recovery with abundant residual oil left underground.

Using the visual etched-glass heterogeneous models, Bahralolom (Bahralolom et al., 1985) observed that the existence of a preferential flow path resulted in early breakthrough and increased CO_2 consumption. However, when 1.5 pore volume (PV) CO_2 was injected, approximately 100% of the oil was removed via a MCM CO_2 flood. In bead-packed models with permeability of 10–25 μm^2, Al Wahaibi (Al Wahaibi and Al Hadhrami, 2011) also found early breakthrough and a delay in recovery with the presence of heterogeneity, but oil recovery still reached nearly 100% for the first-contact miscible (FCM) CO_2 injection. However, the permeability and heterogeneity of those etched and packed models are either undeterminable with enough accuracy or much higher than the actual reservoirs, which would stimulate optimistic recovery compared to the actual field tests (Gao et al., 2014; Cheng et al., 2008; Peng, 2013). Using heterogeneous cores, which are closer to the actual reservoirs in terms of pore structures and permeability, FernØ (FernØ et al., 2015) found that oil recovery was dominated by fracture permeability, and recovery of miscible CO_2 injection in fractures varied from 30% to 90%. Also by CO_2 injection in fractures, Khosravi (Khosravi et al., 2014) found that the miscible CO_2 injection recovery was capable to achieve above 80%. Having one point in common, the studies all agreed that heterogeneity would inevitably lead to early breakthrough as well as increased CO_2 consumption and tail production. As to recovery, it could still reach as high as 80%–100% for FCM and MCM flood (Bahralolom et al., 1985; Al Wahaibi and Al Hadhrami, 2011), indicating that CO_2 could still remove most of the oil from heterogeneous models, which was better than the field tests (with approximately 35%–65% of oil left underground during the miscible CO_2 injection (Enick et al., 2012)). For the immiscible flood in the fractured models conducted by Khosravi (Khosravi et al., 2014), oil recovery was between 8.1% and 23.6%. However, the existing results still have a few limits: 1) the permeability and heterogeneity could not be accurately measured for the etched-glass or bead-packed models used in many studies and 2) it is unclear how the heterogeneity influence oil recovery under different heterogeneity conditions, for the existing results from heterogeneous models are insufficient and overly optimistic compared to actual field applications. In this study, oil recovery of CO_2 injection will be researched using the models that could be accurately measured on the permeability and heterogeneity.

In addition to heterogeneity, CO_2-oil miscibility also affects CO_2 injection in heterogeneous reservoirs. Miscible flooding is believed to be more effective than the immiscible, and its recovery reaches more than 90% in some studies (Bahralolom et al., 1985; Al Wahaibi and Al Hadhrami, 2011; Shedid, 2009), demonstrating its effectiveness. However, the field application results were not so desirable, and approximately 35%–65% of crude oil could be left underground even with a miscible injection due to the low CO_2 sweep efficiency caused by heterogeneity. Some studies also indicated that no oil was recovered when 3 PVs of miscible CO_2 was injected in three split cores after brine flooding (Khosravi et al., 2014; Bikkina et al., 2015). These studies also found that recovery in heterogeneous cores was not as high as 90%, even for the miscible flood, which is a little different from the results reported elsewhere (Bahralolom et al., 1985; Al Wahaibi and Al Hadhrami, 2011; Khosravi et al., 2014). To determine the effects of miscibility on recovery under heterogeneous conditions, MCM and IM CO_2 injection tests were conducted in cores with different heterogeneities. Consequently, the extent to which MCM CO_2 injection is better than IM CO_2 injection was inferred.

As to the injection patterns, many studies have demonstrated that the soaking process and WAG injections are helpful for EOR by extending the CO_2-oil interaction time and increasing the CO_2 sweep efficiency (Li and Gu, 2014; Ma et al., 2016; Yang et al., 2015). To identify the adaptability of the two processes to recover more oil from heterogeneous cores, this research also involved soaking and WAG operations after the primary continuous CO_2 injection.

Additionally, extraction capacity of CO_2 at the MCM and IM pressures was also detected, since extraction is one of the main forms of CO_2-oil interactions influencing CO_2 displacing capacity (Ding et al., 2013; Rudyk et al., 2013). It would be helpful for the understanding of the different displacing capacity of CO_2 presenting in the primary continuous injection, soaking and WAG processes under MCM and IM conditions. Besides, the resulting change of oil composition and viscosity induced by extraction were also measured using the Gas chromatograph and Brookfield viscometer, based on which properties of the left oil in models after CO_2 injection could be indirectly known.

2. Material and methods

2.1. Fluids

Crude oil used for CO_2 flood experiments was collected from the Talimu oil field, China. It was a light oil with a measured density of 862 kg/cm^3 on the ground and viscosity of 4.2 mPa s at 90 °C. The compositional analysis of the crude oil by gas chromatography is presented in Table 1. The purity of CO_2 used in the experiments was 99.99%. The minimum miscibility pressure (MMP) between oil and CO_2 was measured to be 23 MPa at 108 °C via the slime tube method. In regard to the MMP, 15 MPa and 30 MPa were the chosen pressures used for IM and MCM CO_2 floods. To further confirm that the flood at 30 MPa was at the MCM state rather than FCM, the CO_2-oil interfacial tension (IFT) was tested to be 2.1 mN/m at 30 MPa by the axisymmetric drop shape analysis (ADSA) technique (Abedini and Torabi, 2014). Since 0 mN/m IFT is considered to be the criterion for FCM, it was determined that CO_2 injection at 30 MPa was representative of the MCM flood.

2.2. Core block preparation

The cores used in this research were epoxy cemented artificial models, which have been widely applied in laboratory displacement experiments. Eight layered heterogeneous cores with different heterogeneities were employed. Each core had two layers, the low permeability layer (LPL) and high permeability layer (HPL).

Table 1
Oil composition and properties.

Component	wt%	Component	wt%	Component	wt%
nC_5	0.06	nC_{16}	3.77	nC_{27}	0.67
nC_6	1.66	nC_{17}	3.44	nC_{28}	0.61
nC_7	7.43	nC_{18}	0.78	nC_{29}	0.44
nC_8	10.92	nC_{19}	2.55	nC_{30}	0.33
nC_9	11.70	nC_{20}	2.11	nC_{31}	0.33
nC_{10}	11.14	nC_{21}	1.66	nC_{32}	0.28
nC_{11}	10.03	nC_{22}	1.39	nC_{33+}	0.22
nC_{12}	7.82	nC_{23}	1.16	Total	100.0
nC_{13}	6.37	nC_{24}	1.00		
nC_{14}	5.54	nC_{25}	0.94		
nC_{15}	4.88	nC_{26}	0.78		

Property	Value unit
molecular weight	157 g/mol
density (21 °C and P_{atm})	862 kg/cm^3
API gravity	32.6
Viscosity (90 °C and P_{atm})	4.2 mPa s