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Parametric study of oil recovery during CO_2 injections in fractured chalk: Influence of fracture permeability, diffusion length and water saturation

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Experimental secondary and tertiary CO_2 injection tests in fractured, strongly water-wet, chalk core samples were performed to investigate the influence of fracture permeability, diffusion length and initial water saturation on the oil recovery potential. Liquid CO_2 was injected in partially oil and brine saturated core plugs and larger blocks at miscible condition with the oil phase (n-Decane) at 20 °C and 90 bar. High final oil recoveries, up to 100%OOIP, were observed during secondary miscible CO_2 injections in whole, unfractured core samples within 2 pore volumes (PV) injected. High recoveries were also observed in fractured systems (79–93%OOIP), but recovery was less efficient in terms of PV injected (4–12) as a result of increased system permeability and increased diffusion length. Tertiary CO_2 injections in core samples after waterfloods were less efficient in terms of final oil recoveries (62–69%OOIP) compared to secondary CO_2 injections. Additional oil recovery during tertiary CO_2 injection ranged from 0% to 15%OOIP. An adverse effect of water was observed both during secondary and tertiary CO_2 injections, where higher water saturation decreased the oil recovery efficiency by diffusion, indicative of a water shielding effect.

1. Introduction

The rate of new discoveries compared to produced oil reserves has been declining in the last decades (Alvarado and Manrique, 2010), and many of the existing oil fields are approaching the end of waterflooding and are near tail production. Enhanced oil recovery (EOR) processes are designed to maximize oil recovery, extend the field life and increase profitability by extracting the residual oil after conventional recovery methods. One attractive EOR method is the injection of a gas which is miscible with the oil. Depending on reservoir pressure, temperature and oil composition, a range of available gases may develop miscibility with crude oil (Lambert et al., 1996; Skjæveland and Kleppe, 1992). One such gas is carbon dioxide (CO_2). The opposite interests with rising world energy demand and anthropogenic climate change may be combined through Carbon Capture, Utilization and Sequestration (CCUS) to reduce greenhouse gas emissions through safe CO_2 injection and storage in mature oil fields and incremental oil recovery for energy consumption (Falcone and Harrison, 2013). Current CO_2 EOR projects mainly use piped CO_2 from rapidly depleting natural CO_2 reservoirs, and available CO_2 sources are decreasing, which increase the need for anthropogenic CO_2 for CCUS. Injection of CO_2 may be an attractive EOR method depending on the reservoir quality and crude oil, and may favorably change the physical properties of the oil phase to increase flow through 1) oil swelling, 2) reduction of oil viscosity, 3) increased oil density, 4) vaporization and extraction of hydrocarbon components up to C_{30}, 5) reduction of interfacial tension, and, 6) the ability to achieve miscibility with crude oil at relatively low pressure (Holm and Josendal, 1974; Holm, 1976; Skjæveland and Kleppe, 1992; Ahmed, 1994; Lambert et al., 1996).

CCUS, in the form of CO_2 injection for EOR, has been implemented in the US for 40 years, mainly due to the CO_2 availability (from large natural sources and natural gas plants) and extensive CO_2 pipeline infrastructure (Enick et al., 2012; Lambert et al., 1996; N.E.T.L, 2010). In the North Sea, however, CO_2 EOR is still not realized, although identified as a particularly attractive area because of light crude oil and favorable reservoir geology compared with US fields (Blunt et al., 1993). Two Carbon, Capture and Storage (CCS) projects have so far been implemented on the Norwegian Continental Shelf (Eiken et al., 2011), party realized as a result of Norwegian taxation on CO_2 emissions. The current focus on CO_2 capture and storage, might, however, provide a less expensive source of CO_2. With economic incentives, governments can create a demand for CO_2 and contribute to make it a

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commodity (Hustad and Austell, 2004) in a CCUS market. A study indicates that the Ekofisk field, a fractured chalk reservoir located in southern part of the North Sea, is a good CCUS candidate (Jensen et al., 2000), but not economically or technically feasible due to high CO_2 prices and limited CO_2 injection sources and infrastructure. Naturally fractured reservoirs are very heterogeneous in terms of porosity and permeability (Chillenger and Yen, 1983; Fernø, 2012), and the conductive fracture system usually leads to rapidly declining production and low total recoveries (Allan and Sun, 2003; Alvarado and Manrique, 2010). Injection of highly mobile CO_2 leads to gravity induced stabilities and/or viscous fingering (Hirasaki and Zhang, 2004; Lescure and Claridge, 1986) resulting in low macroscopic sweep efficiency and early CO_2 breakthrough. The poor sweep efficiency in heterogeneous reservoirs remains a severe problem, and typically 10–20%OOIP incremental recoveries are reported on the field scale during miscible CO_2 injections (Brock and Bryan, 1989).

The work presented in this paper focus on the influence of fracture permeability, diffusion length and initial water saturation on oil recovery during CO_2 injections in strongly water wet, fractured chalk samples, and is part of a larger, ongoing, experimental program on CO_2 injection for EOR in different oil/brine/rock systems at reservoir conditions (see e.g. Steinsbø et al., 2014; Steinsbø et al., 2015; Fernø et al., 2014; Haugen et al., 2014; Eide et al., 2015a). Within the experimental program both fractured and unfractured core samples are used and several parameters are varied and investigated such as i) different rock types (with a range of different porosity, permeability and wettability conditions); ii) oil composition (pure mineral oils and crude oils); iii) temperature and pressure conditions (CO_2 is injected both in its liquid and in its supercritical state and at both miscible and not miscible conditions with the oil phase); iv) different initial water saturations (secondary and tertiary CO_2 injections) and v) EOR efforts such as CO_2-foam injection for mobility control. Previous work has shown that fractures results in a diffusion dominated recovery process with early CO_2 breakthrough reducing oil recovery both in terms of lower end point final oil recovery and less efficient oil recovery, with a long tail production and several pore volumes of CO_2 injection (Steinsbø et al., 2014).

2. Material and methods

2.1. Rock material

Rørdal chalk core samples were drilled and cut from larger slabs of outcrop rock material obtained from the Portland cement factory at Ålborg, Denmark. The rock formation is of Maastrichtian age and consists mainly of coccolith deposits, and the composition is calcite (99%) with some quartz (1%). The rock is homogeneous on the Darcy scale, porosity and permeability range from 45 to 47% and 3–8 mD, respectively. Details of deposition and diagenetic history may be found in Ekdale and Bromley, 1983 and Hjuler, 2007. The outcrop core material was assumed strongly water-wet based on MRI measurements of wettability and imbibition tests (Johannesen, 2008; Fernø et al., 2010).

2.2. Fluids

The core samples were initially saturated with laboratory made synthetic formation brine or mineral oil (n-Decane). One core sample, block B4, was initially saturated with the high-viscous mineral oil DTE FM 32. Injected CO_2 was in its liquid state and first contact miscible with n-Decane at the experimental conditions 20 °C and 90 bar (Ayirala et al., 2006). Minimum miscibility pressure (MMP) was estimated to 54 bar at 20 °C using CMG Winprop. Viscosities and densities were found in NIST Chemistry WebBook (CO_2 and n-Decane), measured in the laboratory (brine) and provided from supplier (DTE FM 32). Fluid properties and compositions are listed in Table 1.

2.3. Core plug and block preparation

Sixteen core samples (thirteen cylindrical core plugs and three rectangular blocks) were rinsed with water and dried at 80 °C for at least 48 h. Most of the dry core samples were initially saturated with either brine or oil under vacuum, and porosity was determined from weight measurements. Matrix permeability, K_{MAT}, was calculated using Darcy's law during constant flow rate injection with oil (for oil saturated core plugs) and brine (for brine saturated core plugs). Some of the core samples were fractured dry (three core plugs and all blocks) and matrix permeabilities were not measured. The eight core plugs initially saturated with brine were drained with a constant differential pressure gradient of 2 bar/cm to irreducible water saturation (S_{wi}).

Five core plugs were kept unfractured (WHOLE). Eight core plugs (dry or at S_{wi}) were fractured longitudinally with a band saw and thereafter reassembled either with a 1 mm wide polyoxymethylene (POM) spacer to maintain a high permeable, open fracture (OPEN) or without a spacer to get a less permeable, closed fracture (CLOSED). The POM spacer contained separate apertures connected by high conductive flow channels and has been used in several previous experiments without affecting fluid flow (Eide et al., 2015a; b). The procedure to prepare a fractured core plug with a POM spacer is shown in Fig. 1: (A) The core plug was fractured longitudinally. (B) A POM spacer was placed in the fracture. (C–E) The fractured core plug was reassembled and wrapped in aluminum foil. (F–H) Inlet and outlet end pieces were also wrapped in aluminum foil. Before CO_2 injection tests all core plugs were wrapped in aluminum foil to reduce exposure of CO_2 towards the rubber sleeve inside the core holder. The core plugs were placed in the core holder and net confinement pressure of approximately 15 bar was kept constant during all injections. The fractured core plugs were initially flooded with oil to fill the fractures before system permeability after fracturing (K_{FRAC}) was measured during different constant oil flow rates at S_{wi}.

Three larger rectangular blocks were used in CO_2 injection tests and the seven step procedure to prepare and fracture a rectangular block is shown in Fig. 2: (1) A rectangular block was cut from a larger slab of chalk. (2) A band saw was used to cut the block with an interconnected fracture system between injector and producer (identical for all blocks). Both horizontal and vertical fractures were present to increase the tortuosity of the fracture system. POM spacers were placed in each fracture to keep a constant fracture aperture of 1 mm (3) An epoxy layer (<5 mm) was applied using a two component epoxy resin. (4) Aluminum foil was wrapped around the block to reduce CO_2 diffusion out of the block. (5) A second epoxy layer was applied. (6) Aluminum end pieces were attached to the inlet and outlet side of the block. (7) A third and final epoxy layer was applied to hold the end pieces in place. After the seven step procedure the blocks were saturated with oil under vacuum. Block B2 was used in two CO_2 injection tests and both tests had injection start at $S_{oi} = 1$. After the first injection test block B2 was once again saturated 100% with oil. The first and second injection test are referred to as B2 and B2(2), respectively.

Basic core sample characteristics such as size (indicated with diameter (D) for cylindrical core plugs and width and height (W × H) for rectangular blocks), porosity, permeability (both matrix and system permeability after fracturing) are listed in Table 2. The table also shows initial core sample conditions before CO_2 injection start such as fracture state, diffusion length, initial water saturation and oil phase.