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Laboratory determination of oil draining CO_2 hysteresis effects during multiple floods of a conventional clastic oil reservoir

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ABSTRACT

Determination of hysteresis in relative permeability data is useful in obtaining more reliable predictions of water alternating gas (WAG) enhanced oil recovery performance and accompanying associated storage of CO_2. A laboratory-based evaluation of CO_2 draining oil has been conducted on reservoir rocks from a conventional clastic oil reservoir undergoing tertiary CO_2 enhanced recovery. Experimentation was conducted at reservoir conditions of 16 MPa (2300 psi) and 43 °C (110 °F). Through this study, a better understanding of the oil production and associated storage of CO_2 in a conventional clastic oil reservoir has been obtained. Data generated provide an example of a site-specific field project that is currently undergoing a tertiary CO_2-based EOR project demonstrating that associated CO_2 storage will occur. Through multiple cycles of CO_2 injection, this study has shown the effectiveness of first contact CO_2 as it relates to the mobilization of oil from injector to producer. Additionally, in this conventional clastic reservoir, CO_2 trapping appears to have taken place during the initial imbibition cycle, as oil production and differential pressures remain consistent during subsequent tests.

1. Introduction

As part of an ongoing evaluation to demonstrate the potential for the geologic storage of CO_2 associated with CO_2-based enhanced oil recovery, a laboratory study was conducted to investigate the changes in reservoir saturation during multiple cycles of CO_2 injection. Changes in saturation history can be attributed to non-wetting-phase fluids becoming trapped, resulting in the reduction of the in situ wetting-phase fluids. This change in saturation history, and resulting impact on relative permeability, is commonly referred to as hysteresis. This research was conducted to support a modeling and simulation study of an active CO_2 tertiary oil recovery field project using cyclic injections of water and CO_2, commonly referred to as water alternating gas, or WAG. The research was conducted as part of the Plains CO_2 Reduction Partnership Program, one of seven partnerships established by the U.S. Department of Energy National Energy Technology Laboratory Regional Carbon Sequestration Partnership Initiative.

During the multiple cycles of CO_2 injection that are used for tertiary recovery of oil from a reservoir, it is expected that a reduction in the permeable pathway of the pore network will occur. This reduction occurs because the wetting (oil or water) phase fluid can trap some of the nonwetting (CO_2) phase fluid and result in a change to the conductivity of the pore network, which has a net effect on the relative permeability of the fluids in the rock (Fatemi et al., 2012). In addition, capillary pressure hysteresis can occur because of variations in the contact angle between the wetting fluid and the rock that occur during drainage and imbibition. During drainage, the wetting fluid is being pushed back from rock surfaces, causing a receding contact angle, whereas during imbibition, an advancing contact angle is created. Capillary pressure hysteresis also causes hysteresis in the relative permeability curves (Anderson, 1987), and it has been shown by Fatemi et al. (2012) that the shapes and end points of the relative permeability curves can change slightly during subsequent drainage and imbibition cycles. The amount of hysteresis and its variation due to multiple water and gas cycles is important to understand to properly model associated CO_2 storage, as the effect is usually pronounced when liquid and gas occupy the same system and may have direct implications to CO_2 migration and trapping in the pore spaces (Burnside and Naylor, 2014). In this paper, we describe an investigation of residual trapping in oil reservoir rocks as determined through measurements of hysteresis effects in the relative permeability of oil, water, and CO_2 during multiple drainage and imbibition cycles in four sandstone reservoir rock core

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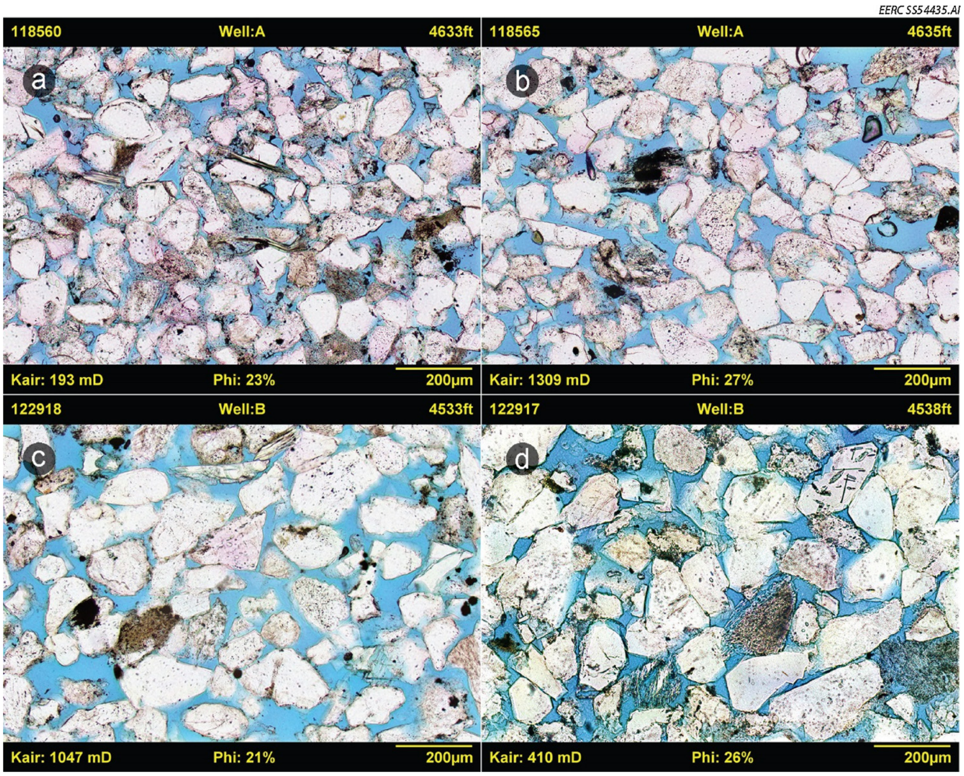

Fig. 1. Thin-section photomicrographs showing the variability in grain and pore sizes throughout the vertical succession of the reservoir. Fig. 2a and b represents Well A and demonstrate the difference in pore throat size and connectivity causing (blue) the reduced permeability. Fig. 2c and d is from Well B and show a similar trend (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
Porosity and Permeability for the Ten Plug Samples That Were Downselected from the Two Site Cores. Four (shaded) were selected and tested to determine the hysteresis effect of cyclic CO_2 and water injection.

Sample No.	Well	Depth, m (ft)	Porosity, %	K_{air}, mD
118556	A	1410 (4626)	24	119
118560	A	1412 (4632)	23	193
118561	A	1412 (4632)	25	263
118565	A	1413 (4635)	27	1309
118568	A	1413 (4637)	23	719
122918	B	1382 (4533)	26	1047
122915	B	1382 (4535)	25	1126
122916	B	1383 (4536)	25	1525
122919	B	1383 (4536)	24	1455
122917	B	1383 (4538)	21	410

plugs.

2. Background

Injection of CO_2 into an oil reservoir increases near-wellbore CO_2 saturation while concurrently decreasing brine/oil saturations. This fluid displacement process results in an increase in the fraction of the overall pore space available to CO_2 and a subsequent increase in the permeability of CO_2 relative to the other pore fluids. During post-injection periods, saturation changes move in the opposite direction. CO_2 migrates away from the injection point, decreasing the CO_2 saturation and increasing the brine/oil saturations. This results in a decrease of the relative permeability of CO_2. As CO_2 saturation continues to decrease, a “residual” saturation will eventually be reached at which time the CO_2 is effectively immobilized by capillary forces and, therefore, indefinitely trapped Krevor et al. (2012); Metz et al. (2005). To predict the extent of CO_2 migration within the reservoir under the effects of residual trapping requires an estimate of residual CO_2 saturation. Previous studies have shown that residual CO_2 saturation may be on the order of 5%–30%, varying with reservoir conditions such as mineralogical reservoir homogeneity, direction of flow (i.e., perpendicular or parallel to bedding), and grain size and sorting. (Al-Menhali and Krevor, 2016; Ennis-King and Paterson, 2001; Krevor et al., 2015; Niu et al., 2015; Zuo and Benson, 2014).

Since its discovery, the oil reservoir in this study has undergone primary production (solution gas drive) and waterflooding, resulting in the production of about 37% of original oil in place (OOIP). Large-scale miscible CO_2 flooding has also been implemented in the field in multiple phases. It is anticipated that an additional 10%–15% of the OOIP will be recovered from the reservoir using CO_2-based enhanced oil recovery (EOR). Since the field is being operated in a WAG process, relative permeability hysteresis is likely to be an important mechanism affecting both oil production and associated CO_2 residual trapping and storage in the reservoir.

3. Sample selection

During the development phase of the tertiary oil recovery project, two wells were drilled and cored to obtain new petrographic and petrophysical reservoir properties, monitor CO_2 movement, and provide insight regarding incremental oil recovery. Core plug samples were acquired from each of the two wells located within the active CO_2-flooding area of the field. The lithology of the reservoir intervals and the geologic heterogeneity present were considered during sample selection. Specifically, there are three distinct flow units in vertical succession within this reservoir. The reservoir is dominated by clastic sandstone intervals that are interbedded with clay-rich lenses. This is an important aspect of the geology when considering lateral and vertical CO_2 movement and how it may impact both oil productivity and the associated storage potential of CO_2. Fig. 1 illustrates the variability of grain size, pore filling, and mineralogical differences observed through petrographic thin-section analysis of the cores. To ensure the study considered this heterogeneity, ten samples were selected from each well to assess the range of porosity and permeability within the reservoir and to provide a representative data set for future modeling and simulation activity. Table 1 presents the results of the routine core analyses conducted to determine porosity and permeability for these ten samples. These data were analyzed and provided the basis for