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Laboratory Investigation of Wall Creek Formation Performance on Combined Oil Recovery and CO_2 Storage within the Residual Oil Zone Fairways of the Powder River Basin, Wyoming

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Abstract

As the world transitions toward net-zero emissions, integrating carbon capture and utilization strategies into petroleum production processes is essential for reducing carbon intensity. This study investigates the potential of combined CO_2-enhanced oil recovery (CO_2-EOR) and storage within the residual oil zones (ROZ) of the Wall Creek Formation in Wyoming's Powder River Basin. Multi-phase core flooding experiments were conducted to evaluate CO_2 performance in terms of oil recovery and storage capacity across various sandstone facies. The experiments utilized core samples representative of the basin's depositional environments and involved measuring fluid properties, relative permeability, and recovery factors under reservoir conditions. Results indicate that medium-grained distributary complex sandstones exhibit superior permeability and recovery efficiency, achieving up to 68.7% recovery and 28.8% CO_2 storage potential. Comparatively, tidal shoal facies demonstrated lower recovery and storage capacities due to finer grain size and reduced permeability. These findings underscore the viability of optimized CO_2-EOR and storage in sandstone ROZ fairways, advancing the understanding of subsurface carbon storage in challenging clastic reservoirs.

Introduction

Although the world is accelerating toward net zero, fossil fuels are expected to remain in use for the foreseeing future. Therefore, incorporating technologies that reduce carbon intensity in petroleum production can play a significant role in the energy transition. One such technology, combined CO_2

enhanced oil recovery (EOR) and storage, not only increases oil production but also contributes to a negative carbon balance by storing CO_2 underground. The injected CO_2, when trapped in subsurface reservoirs, can offset the emissions caused by the combustion of the produced oil. Residual oil zones (ROZ) have been proven to be economically viable targets for CO_2-EOR. Notably, significant ROZ fairway resources exist in Wyoming's Powder River Basin. For example, 10 large oil fields with tilted oil-water contacts are found along the 54-mile Salt Creek/Teapot Dome to South Glenrock/Big Muddy trend in the southern part of the basin. These fields contain over 3 billion barrels of original oil in place and have already produced more than a billion barrels, providing strong confidence in the area's potential as a major ROZ fairway resource. In this project, a multi-phase core-flooding experiment was conducted to determine the CO_2 performance on oil recovery and carbon storage events in the Wall Creek ROZ reservoir.

Methods

The core plugs were selected based on the following steps. First, gamma-ray, core description and UV light appearance suggested three major intervals, including 1865–1880 ft. (MD), 1880–1910 ft. (MD), and 1910–1965 ft (MD). Second, for each interval, cores that are oil-rich under UV light and porosity and permeability illustrative were selected. These core plugs were drilled from the whole core and cleaned by CoreLabs (Denver). The core plugs had similar dimensions of around 5.184 cm in length and 3.735 cm in diameter. The normal hydrostatic pressure gradient of 0.433 psi/ft was chosen for experimental purposes even though previous data showed the under-pressure behavior for the nearby wells with gradient averaged at 0.302 psi/ft (Toner, 2019). The temperature was estimated from the well log (API#: 49-025-24128). A summary of the petrophysical properties of all the cores in this study is shown in **Table 1**.

Table 1. Petrophysical data of the cores utilized in flooding experiments.

Core Sample #	Depth (ft)	Pressure (psi)	Temperature (°C)	Length (cm)	Diameter (cm)	Porosity (%)	Klinkenberg Permeability (mD)	Pore volume (cm^3)
50	1871.20	810.23	38.0	5.154	3.750	18.34	11.3	10.384
65	1886.35	816.79	38.2	5.279	3.722	21.80	275	12.216
139	1961.30	849.24	39.0	5.120	3.732	18.05	15.4	10.068

In this work, the water sample statistics of the synthetic formation water (SFW) are obtained from Appendix F5 of the Platte River Basin Water Plan Update Report (Hallberg & Clark, 2013) and the water formulation is estimated as in **Table 2**. The density and viscosity of the formation water and crude oil used throughout the core flooding experiments are shown in **Table 3**. The Wall Creek crude oil was collected from the separator of a nearby well (API# 49-025-05090) about a mile south of the coring well. High-purity carbon dioxide (99.99%) was supplied by Rocky Mountain Air Solutions.

Table 2. Synthetic formation water formulation for Wall Creek Sandstone.

Component	KCl	NaCl	$CaCl_2 \cdot 2H_2O$	$MgCl_2 \cdot 6H_2O$	Na_2SO_4	Na_2CO_3	$NaHCO_3$
Concentration (mg/L)	9.53	1020.80	22.01	16.73	219.29	0.32	2533.06

Table 3. Fluid properties of synthetic formation water and crude oil used in this study.

Temperature	Property	Crude Oil	Water
21 °C	Viscosity (cP)	3.2638	0.9849
	Density (g/cm^3)	0.8222	1.0036
38.5 °C	Viscosity (cP)	2.2012	0.6773
	Density (g/cm^3)	0.8095	0.9981

The flow experiments for oil recovery and CO_2 storage evaluations were conducted using the high-pressure and high-temperature core flooding system shown in **Figure 1**. Three dual-cylinder pumps (Vindum and Teledyne Isco) were utilized to inject water, crude oil, and CO_2. A Rosemount™ pressure transducer with a range of 0–2,000 psi was used to measure the differential pressure across the core plug. Another two Teledyne ISCO pumps were used to maintain a constant net confining pressure of 1,000 psi during the experiments and set the backpressure regulator pressure. The core holder and fluid accumulators were placed in a Memmert UF750 oven to control the temperature at ~38.5 °C throughout the flooding experiments, where room temperature was averaged at 21 °C for reference.

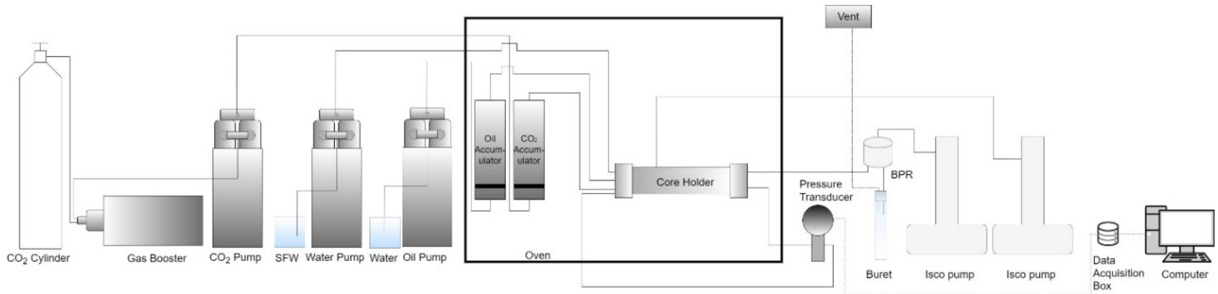

Figure 1. Schematic of the high-pressure and high-temperature core flooding setup.

The core plugs were prepared by wrapping each of them with Teflon tape, aluminum foil, and a shrink tube after cleaning and drying. Vacuum saturation with SFW was commenced for the three cores using a vacuum pressure of -11.6 psi overnight. The porosity of the cores was double-checked using their dry and water-saturated weights. Crude oil was vacuum filtered with a 0.45-micron pore size membrane.

A 100% water-saturated core was loaded into a Hastelloy core holder and placed into a Memmert oven in the horizontal position. The temperature of the oven was set to the cores' respective temperatures. The pore pressure was fixed at the cores' respective reservoir pressures, and the net confining pressure was controlled at 1,000 psi throughout the flooding experiment. The brine permeability of the core samples was evaluated by measuring the pressure drop across the core at different brine injection flow rates. Oil drainage was then performed to establish $S_{w_{ir}}$. This flow rate was modified, accommodating varying core permeabilities in three experiments. After the oil drainage, the core was flushed with oil at minimum flow rates for 2-3 weeks (Al-Ameer et al., 2023) to alter the wettability and reduce $S_{w_{ir}}$. After aging, oil drainage was performed again to obtain the oil permeability at $S_{w_{ir}}$. Once finished, CO_2 was injected into the core for the relative permeability measurement, adopting the Johnson-Bossler-Naumann (JBN) unsteady-state method. The fitting curves were estimated with a modified Brooks Corey (MBC) model (Behrenbruch & Goda, 2006a; Johnson et al., 1959):

$$krg = krg_{max} \cdot \left(\frac{S_g - S_{g_c}}{S_{g_{max}} - S_{g_c}}\right)^{n\_gas} \quad \text{(Eq. 1)}$$

$$kro = kro_{max} \cdot \left(\frac{S_{g_{max}} - S_g}{S_{g_{max}} - S_{g_c}}\right)^{n\_oil} \quad \text{(Eq. 2)}$$

$$S_{g_{max}} = 1 - S_{or} - S_{wir} \quad \text{(Eq. 3)}$$

In our case, $S_{g_c} = 0$. krg_{max} is the end point gas relative permeability normalized to water permeability at $S_{w_{ir}}$ and S_{or}, while kro_{max} is the end point oil relative permeability normalized to water permeability (Behrenbruch & Goda, 2006a; Kamali et al., 2015). The oil recovery was monitored for each injection scenario, and the core-scale CO_2 storage was quantified using mass balance.

Results

The CO_2-oil relative permeability result is displayed in **Figure 2**. The rock samples experienced forced imbibition and behaved less water-wet after aging, thus lower $S_{w_{ir}}$. Once $S_{w_{ir}}$ established, CO_2 injection was conducted. At the end of the CO_2 injection, the CO_2 saturation/CO_2 storage potential (Yu et al., 2023) and residual oil saturation S_{or} were determined. Oil recovery factor (RF) after CO_2 injection without prior water flooding was also calculated based on the established original oil in place (OOIP). All these parameters are listed in **Table 4**.

There are four dominant facies for the whole core, where distributary complex and tidal shoal facies lead the main ROZ. It is found that the distributary complex facies that contains the medium-grained, clean sandstone has the best permeability among all facies. Although high permeability made it less efficient to establish the $S_{w_{ir}}$ to restore the ROZ wettability, CO_2 was able to flush the oil that occupies the pore body easier during the restoration process, which leads to the highest recovery factor of 68.7% and CO_2 storage potential of 28.8%. Tidal Shoal facies contains very-fine to fine grained sandstone and it is less permeable. $S_{w_{ir}}$ was able to achieve lower, however, less oil could be recovered due to the more oil-wet behavior after the restoration and also less space was made for the CO_2 to be stored, where recovery factor is averaged at 54.1% and CO_2 storage potential at 25.6%. Note the oil saturation of the raw core measured after drilling and the residual oil saturation, S_{or}, estabilished during this study for distributary complex and tidal shoal facies are 0.11/0.13 and 0.22/0.19, respectively, which might roughly suggest the oil recovery potential in tidal shoal facies.

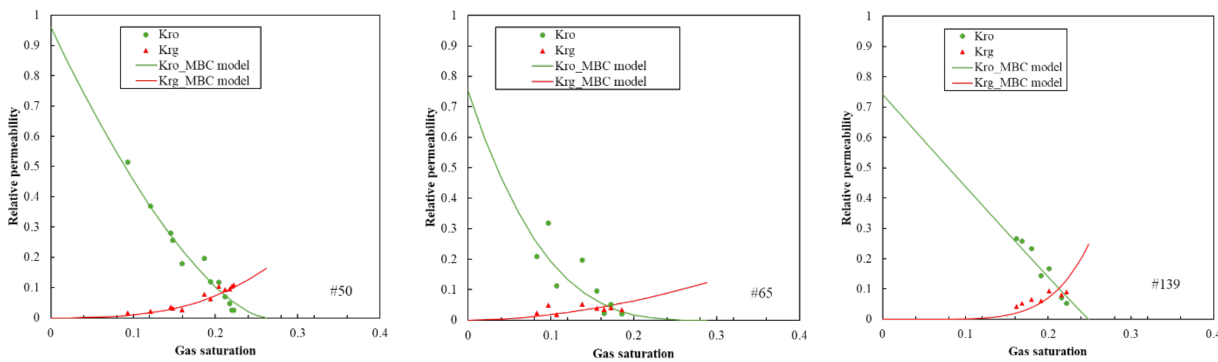

Figure 2. CO_2-oil relative permeability result for core sample #50 (left), #65 (middle) and #139 (right).

Table 4. Major parameters and findings from the core flooding experiments.

Sample	**#50**	**#65**	**#139**
Water permeability (mD)	4.172	162.041	5.421
$S_{w_{ir}}$	0.535	0.581	0.519
kro_{max} @ $S_{w_{ir}}$	0.960	0.751	0.741
S_{or}	0.203	0.131	0.232
krg_{max} @ $S_{w_{ir}}, S_{or}$	0.164	0.123	0.249
$S_{CO_2\_max}$/**CO_2 storage potential**	0.262/26.2%	0.288/28.8%	0.249/24.9%
Recovery Factor	56.3%	68.7%	51.8%

Conclusions

The results obtained provide essential information for assessing the technical and economic viability of implementing a highly optimized CO_2-EOR project, along with associated CO_2 storage, in the ROZ fairway near Salt Creek—the largest oil field and main pay zone CO_2 flooding site in the Rocky Mountain region. Finally, this will be the first of several ROZ fairway projects that address clastic/sandstone oil formations that face more challenging residual oil saturation settings. Carbonate/dolomite ROZs resource settings have already been extensively addressed in the Permian Basin. Much of the remaining oil resources and associated CO_2 storage capacity in the U.S., along the Gulf Coast, East Texas, Mid-Continent, and Appalachia, are in sandstone formations that would further benefit from this work.

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