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Effect of petrophysical matrix properties on bypassed oil recovery from a matrix-fracture system during CO_2 near-miscible injection: Experimental investigation

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ABSTRACT

The effects of petrophysical matrix properties such as porosity and permeability on bypassed oil recovery were investigated during CO_2 injection in fractures at different miscibility regimes (first-contact miscibility, near-miscibility, and immiscibility). A special experimental setup was designed for this purpose and a series of CO_2 injection experiments were performed using two different types of porous media, sandstones and carbonates. To confirm the analysis, some tests were repeated in the presence of irreducible water saturation. In addition, dimensional analysis was used to capture the dominant forces and mechanisms.

The results demonstrated that the highest oil recovery was achieved within near-miscible regime for the both rock types. Furthermore, in all miscibility regimes, the oil recovery factor decreased with the increase of the rock complexity and frequency of dead-end pores, whereas it declined as the permeability decreased. However, differences in recovery factors of near-critical and super-critical tests grew. Considering the analytical calculations and the results of experiments including initial water saturation, it can be concluded that near-critical point wetting and the number of dead-end pores have significant effects on variations of the oil recovery factor. With near-critical point wetting, maximum recovery was achieved at near-critical state, and the presence of dead-end pores caused the role of this mechanism to be more noticeable. As a result, differences in the recovery factor of near-critical and super-critical tests grew.

1. Introduction

Gas injection is one of the most common enhanced oil recovery methods. Conventional gas injection in carbonates leads to a low recovery factor due to different permeabilities of matrix and fracture and also high capillary forces. The residual oil can be recovered by dispersion/diffusion (Hara and Christman, 1993), pressure (Pande and Orr, 1990), gravity (Firoozabadi and Tan, 1994) and capillary (Fayers and Lee, 1992) drive mechanisms.

Gravity drive is one of the most effective methods in the recovery of bypassed oil, which is limited by capillary forces. This limitation is amplified in small, low-permeability blocks, which counterbalances the gravity drive (Thomas et al., 1991). Hence, the secondary and the tertiary gas gravity drainage will be absolutely effective by reduction of the interfacial tension (IFT) (Firoozabadi and Tan, 1994; Karimaie and Torsæter, 2010). On the other hand, since the minimum miscibility pressure (MMP) of CO_2 gas injection is lower than other gases, it could be a really useful option in low-permeability reservoirs (Holm and Josendal, 1974).

In this study, near-miscible injection is considered as a near-critical injection that the two-phase interface exists but the IFT is very low. In a near-critical condition, either oil or gas is spread on the medium (water or rock) and a continuous thin film is formed. This phenomenon, named as the near-critical-point-wetting, was first reported by Cahn (1977). Accordingly, in normal systems, where two phases A and B are present in contact with a third solid phase (S), the following inequality holds true:

$$|\sigma_{SA} - \sigma_{SB}| < |\sigma_{AB}| \quad (1)$$

As the pressure increases, both sides of the aforementioned inequality fade, however the term σ_{AB} declines at a higher rate. Therefore, in the vicinity of the critical condition, we can write:

$$|\sigma_{SA} - \sigma_{SB}| = |\sigma_{AB}| \quad (2)$$

which is the required condition of fluid spreading.

In the near-critical situation, the gas–oil contact is increased due to the spread of oil on rock surface. This promotes

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Nomenclature

C	concentration in mobile fluid
Co	feed concentration
D	dispersion coefficient
f	fraction of pore space occupied by mobile fluid
FCM	first contact miscible
g	gravity constant
H	matrix height (core diameter)
I	pore volume injected, (Vt/L)
IFT	interfacial tension
IM	immiscible
K	permeability
L	characteristic length (or core length)
MMP	minimum miscibility pressure
NM	near-miscible
NpcG	ratio of capillary to gravity forces
Pc	capillary pressure
r	hydraulic radius
t	time
v	rate of fluid flow in porous media
V	average interstitial velocity
x	distance from inlet end of core
y	dimensionless distance, x/L
γ	VL/D
μ	viscosity
ρ	density
σ	interfacial tension
φ	porosity

vaporization and eventually leads to higher oil recoveries. A number of previous experimental and simulation studies suggest that the near-miscible gas injection is more efficient than the first-contact miscible gas (Burger et al., 1994, 1996; Khosravi et al., 2014; Pande, 1992; Sohrabi et al., 2008a, 2008b; Thomas et al., 1994). Pande (1992) and Burger et al. (1994) in their simulation studies showed that the highest recovery is yielded at pressures lower than the required MMP.

Campbell and Orr (1985) investigated the oil recovery by CO_2 gas injection in a micromodel. In this case, the entire oil in place was produced only within five minutes. Although they injected CO_2 at higher pressures than MMP, the observed flow regime in the dynamic condition was near-miscible owing to the oil-gas contact forming thin films on the pore walls. Sohrabi et al. (2008a) showed that the near-miscible injection leads to the production of the entire oil in contact in pore scale using a micromodel. They claimed that a different mechanism contributes to oil production in near-miscible injection which is due to the low gas-oil IFT, complete wettability, and simultaneous flow of gas and oil in pore scale.

Burger et al. (1996) performed the required experiments for evaluation of mass transfer from the bypassed zones to the flow zones. Although they achieved the highest oil recovery in the first-contact miscible injection, they showed that mass transfer is remarkably high in near-miscible injection on an experimental scale. Khosravi et al. (2014) studied the importance of active forces in cross-flow from the bypassed zone to the flow zone in a matrix-fracture system. They concluded that the highest recovery is obtained in the near-miscible injection owing to the dominating mechanism of vaporization, which is enhanced in the near-miscible conditions as a result of the near-critical-point wetting phenomenon.

As it was mentioned previously, many experimental studies have investigated the active mechanisms involving in the recovery of the bypassed oil in the matrix-fracture system. It must be noted that the majority of these studies used a sandstone core with high permeability as the matrix, and yet no study has investigated the influence of the petrophysical properties of the matrix, like permeability and porosity, on the recovery of bypassed oil. Therefore, in addition to using sandstone with high permeability as the matrix, this study used a low permeability carbonate, and CO_2 gas in different injection regimes namely the first-contact miscibility, the near-miscibility and the immiscibility, was injected into the fracture.

In the carbonate core, because of the reduction in permeability as well as rock tortuosity (increased dead-end pores) compared with the sandstone core, the distribution of fluid in the matrix changes and affects the recovery mechanisms. In the current study, the dimensional analysis was carried out to evaluate mechanisms affecting the production of bypassed oil. In addition, to confirm the taken assumptions and analyses, the gas injection tests were repeated for the both sandstone and carbonate cores, in the presence of irreducible water saturation.

The flow regimes are defined and selected on the basis of the IFT values. Experiments are defined in three cases of first-contact miscible (IFT = 0), near-miscible (IFT close to zero) and immiscible (IFT greater than zero). It is noteworthy that this classification is already used by other researchers (Khosravi et al., 2014; Sohrabi et al., 2008a, 2008b). For better understanding of all simultaneous processes in the system, it is essentially important to characterize the phase behavior of the existing fluid system. Therefore, we have conducted experiments using a simple hydrocarbon system at constant pressure and temperature.

Table 1
Properties of cores.

Material	Sandstone	Carbonate
Diameter (cm)	3.8	3.8
Length (cm)	8	8
Porosity (%)	17.6	22.13
Permeability (md)	150	8.26
Irreducible water saturation (%)	35	34

2. Rock and fluid properties

The properties of carbonate and sandstone cores used in our experiments are listed in Table 1. The permeability of the carbonate core is 8.26 mD, which is lower than that of the sandstone core. Because only two cores were used during experiments, the condition of the cores had to be kept the same in all experiments, which means that preparation, rock cleaning, and wetting conditions were identical. After each experiment, the cores were washed with isopropanol by ten times the volume of the pores injected, and they were dried for 24 h in the oven. For the next experiment, the cores were vacuumed for 24 h and then saturated to the desired fluid. Before each experiment, the core permeability and porosity were measured to ensure the stability of the rock properties. Practical application of cores has been explained in the experimental design section.

Decane has been used as the synthetic oil which is recovered by CO_2 gas injection in the fracture. In order to determine the thermodynamic properties of the system (including IFT, formation volume factor and densities), a binary system has been used. All experiments were performed at the constant temperature of 80 °C. According to the previous studies on the decane-CO_2 system (Cismondi et al., 2012; Khosravi et al., 2014), the critical pressure is equal to 14.24 MPa at 80 °C. Hence, our experiments were performed under three pressures of 15.86, 13.79 and 13.1 MPa, representing first-contact miscible, near-miscible and immiscible,