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Mechanistic investigation of bypassed-oil recovery during CO_2 injection in matrix and fracture

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HIGHLIGHTS

- CO_2 injection has been investigated experimentally, for both fracture and matrix systems.
- Different driving forces has been studied using a system of hydrocarbon component.
- During CO_2 injection in fracture, near-critical test provided the highest recovery.
- During CO_2 injection in matrix, the maximum recovery was achieved for the FCM displacement.

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ABSTRACT

CO_2 injection is currently one of the most popular EOR (Enhanced Oil Recovery) methods in the world, as its MMP (Minimum Miscibility Pressure) with oil is lower than other common injected gases. In this work, miscible, near-miscible and immiscible CO_2 injection was investigated experimentally for both fracture and matrix systems. Different driving forces (such as diffusion, gravity, viscous and capillary) were studied with a system of hydrocarbon components with well-known properties in porous media, following a rational design and procedure. To ensure experiments were representative of reservoir conditions and to demonstrate the relative importance of active forces, pore and core scale dimensional analyses were conducted.

During CO_2 injection in fracture, near-critical tests provided the highest recovery. Significant impact of gravity, swelling and vaporization was inferred from "ultimate recoveries," "variations of pore pressure," "the status of oil production," "recovery rate of corresponding pre-equilibrated test," and "dimensional analysis." In CO_2 injection in matrix, the maximum recovery was achieved for the first-contact-miscible displacement, as a result of IFT (Interfacial Tension) reduction.

1. Introduction

Gas injection is a favorite method of oil recovery that is widely used for conventional or fractured reservoirs in industry. During injection, gas flows through highly permeable paths; as a result, reservoir oil may be bypassed in lower permeable zones. This could happen in microscopic or macroscopic dimensions that include not only rock heterogeneities but also fluid heterogeneities such as viscosity or density.

Molecular diffusion/dispersion and cross-flows (viscous [1], capillary [2] or gravity [3] driven) help the bypassed oil to be recovered. When the injected gas is CO_2 swelling and vaporization [4] improve the recovery as well. In addition, elements such as: presence of connate water, injection type (first-contact-miscibility, near-miscible and immiscible injection) and existence of dead-end pores may affect the recovery process [5]. Near-miscible injection is an attractive choice for conventional reservoirs, as it has the advantage of decreasing capillary threshold, increasing the assessable oil in place, and lower gas compression costs [6]. Furthermore, in fractured reservoirs near-miscible injection provides the industry with optimum costs and a gravity head for an acceptable rate of oil drainage from the matrix [7].

Usually miscibility regions are distinguished by the ratio of injection pressure to Minimum Miscibility Pressure (MMP), measured by the slim-tube test known as thermodynamic MMP [8]. Many authors; however, have questioned the miscibility obtained in porous media at suggested pressures; for example, Campbell and Orr [9] and Mohanty et al. [10] investigated miscible CO_2 injection (injection pressure was above thermodynamic MMP) in a dead-end-pore micro-model and reported the existence of an

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Nomenclature

v	rate of fluid flow in porous media
μ	viscosity
ρ	density
g	gravity constant
D_h	hydraulic diameter of pores
D_{CO2}	diffusion coefficient of CO_2 into oil phase
L	characteristic length (or Core length)
S_o	oil saturation changes
P_{cd}	capillary threshold pressure
P	pressure
D	core diameter
K	permeability
φ	porosity
Q	rate of oil displacement
N_{cv}	ratio of capillary to viscous forces
N_{PcG}	ratio of capillary to gravity force
N_{gr}	ratio of gravity to viscous force

interface between the oil and gas phases. In porous media, when the fluids flow through rock heterogeneities, the equilibrium path is affected by mixing streams that not only disperse the components within the phases but also change the oil and gas multi-contact sequences [11].

To avoid the complexity of simultaneous interactions of different phenomena (such as gravity drainage, multi-contact miscibility, (Interfacial Tension) IFT changes, capillary-related mechanisms, vaporization and swelling) during CO_2 injection (especially in fractured systems), it is wised to use the advantages of a simple system of hydrocarbon to control the condition of the experiment and get a better image of the process [5,10,12–16].

In 1977 Cahn showed analytically that at the near-critical state of oil and gas phases, the oil phase may change into a continuous film that is dispersed through the porous media and is spread on the other existing phases such as rock or water [17]. He called it "near-critical-point wetting" and many authors have captured images of such phenomena in micro-models [16,18,19].

In the current study, the defined miscibility region is based on the amount of IFT. Therefore, theoretically, three different regions can be distinguished; miscible (above critical point), immiscible (below and far-from-critical point) and near miscible (below and near-critical point). In order to make sure that in each test the value of IFT in porous media is estimated with acceptable precision, two-component experiments are conducted at fixed temperature and pressure. Consequently, the system's thermodynamic degree of freedom is zero and IFT has a constant value during each test.

A primary version of the setup used in this work was introduced by Morel and colleagues in 1993 [12]. It was later modified by Le Romancer et al. and Burger [14,3].

The present paper attempts to use descriptions in the literature and thermodynamics to produce a well-defined component system, designing controlled tests in porous medium in high-pressure, high-temperature conditions. In the light of the experimental results, the role of forces (such as gravity, capillary and viscous), and activated mechanisms (such as swelling and vaporization) are studied in a wide range of dimensionless numbers.

2. Materials and methods

2.1. Fluid properties

Decane was selected as the model oil, and carbon dioxide was injected as a gas, either in matrix or fracture, at 80 °C. Physical properties of the selected systems were calculated by PVTi software and the three-parameter Peng–Robinson equation-of-state (EOS) [20]. The volume shift technique [21] was used to match the reported molar liquid densities [22] of the pure components up to their critical points, and no other tuning parameters were used. During the design of experiments and analysis of results, this model was used to predict oil/gas properties such as density, viscosity and molar volume and also the results of tests such as swelling factor and saturation pressure for different portions of gas mixed with oil.

Based on Cismondi et al. [23] and results of EOS, at 80 °C, the critical pressure of the CO_2/C10 system was 14.24 MPa; hence, 15.86, 13.79 and 11.03 MPa corresponded to first-contact-miscibility injection, near-critical injection, and far-from-critical injection, respectively. This classification can be confirmed by investigation of IFT variation vs. pressure, as shown in Fig. 1. In this graph, experimental values of IFT [24] are compared with those predicted with the Parachore model [25], and it is shown that the calculated values are in reasonable agreement with the measured data.

2.2. Experimental setup

Fig. 2 shows the schematic of the experimental setup. Core holder, back-pressure-regulator (BPR) and transfer-vessels were located inside the oven. Fluids were injected into core or fracture by positive-displace pumps at a constant rate, and BPR guaranteed the stability of test pressure. The liquid and gas produced were collected in a graduated glass and a gas-meter, respectively. A condenser was mounted on the gas stream of the separator to accelerate condensation, prevent oil from entering the gas-meter, and keep the gas stream at ambient temperature (about 22 °C) by water circulation. Data such as fracture pressure, differential pressure (DP), and temperatures were recorded by means of a data acquisition system coupled with a computer. The differential pressure transducer was designed to operate in the range of −0.7 to 0.7 kPa with an accuracy of ±0.1 kPa. The transducers have the capability of measuring pressures up to 20 MPa with the accuracy of 0.1% of their full scale.

Fig. 3 shows an empty gap with thickness of 0.3 cm, at one end of the core holder as the fracture plane. Fluids could be injected into matrix or fracture using input-1 or input-2 (Fig. 3). The output line was attached to the fracture, below the input-2. In addition, to

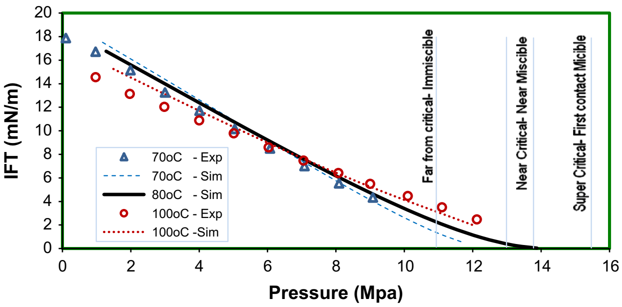

Fig. 1. IFT variations vs. pressure for a fluid system of CO_2/C10, based on experimental results [24] and simulation estimations.