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# Low IFT gas–oil gravity drainage in fractured carbonate porous media

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ABSTRACT

This paper addresses a study of gas–oil gravity drainage in fractured carbonate rock subjected to gas injection in low interfacial tension. The purpose of the experiments described in the paper was to investigate gas injection in fractured carbonate reservoirs in both secondary and tertiary cases (after water injection), focusing on gravity drainage using equilibrium gas followed by re-pressurization. Gas injection experiments were performed on 20 cm long and low permeable outcrop chalk core surrounded with a fracture established with a novel experimental set-up in reservoir conditions. The core was saturated with binary mixture live oil consisting of $C_1$ and $C_7$ of a known composition, while the fracture was filled with sealing material to obtain a homogeneous saturation. After core initialization, the sealing material was removed by increasing the temperature to higher than its melting point and displaced by live oil. Gas was then injected into the fracture and gravity drainage experiments were performed in low interfacial tension (<0.5 mN/m) where the IFT between the phases were measured experimentally by selecting the proper pressure and temperature.

Experiments were performed at different pressures and reversibility of the effect of the interfacial tension was checked by re-pressurization process. The oil recovered from the bottom side of the block was measured versus time.

Based on the results of this study, the recovery of oil showed a significant increase by re-pressurization in gravity drainage process. It was also clear that low IFT gravity drainage is capable to recover a significant amount of oil in fractured reservoirs even after water injection.



## 1. Introduction

Gas injection is an efficient IOR method increasingly applied as a secondary or tertiary oil recovery scheme, especially for fractured reservoirs. It has been reported that large amount of oil may be trapped in fractured reservoirs due to capillary forces and gas injection could be an efficient recovery method for such reservoirs. In this case, gravity drainage is a mechanism that would help to recover the oil. Gravity drainage is one of the most important processes taking place in fractured reservoirs and it plays a major role in oil recovery from low permeability matrix blocks during gas injection process. Gravity drainage is responsible for production from various gigantic reservoirs in southern part of Iran which are over half a century old.

A matrix block surrounded by gas, will undergo a gravity drainage process when the gravitational forces exceed the capillary forces. The density difference between the gas in the fracture and the oil in the matrix is the main driving force, which is counteracted by the matrix capillary pressure. In this process, recovery rate is characterized by an initial period of a constant maximum rate, with gradual decline toward zero.

Very few laboratory works describing the flow mechanism taking place in gravity drainage have been published. Cardwell and Parsons (1948) were the first researchers to describe the concept of gravity drainage theoretically. Dumore and Schols (1974) reported low residual oil saturation of 5% in high permeability sandstone subjected to gravity drainage. Hagoort (1980) found that gravity drainage could be a very effective oil recovery process and reported several measured recovery–time curves for different core samples using a centrifuge. He also proposed a new method for calculating oil relative permeability in gravity drainage process. Firoozabadi et al. (1988) performed several experiments for a variety of samples using centrifuge. In these experiments cores were saturated with water and then displaced with pure heptane. The measured early points of the recovery curves are somewhat below the values expected in their experiment. The experiments have been simulated by Firoozabadi and Aziz (1991) using a least squares technique and varying the Corey exponent *n*.

Thiebot and Sakthikumar (1991) performed gas–oil gravity drainage experiments under reservoir conditions in fractured system using cylindrical cores having both lateral and horizontal faces open to flow. They used a permeable limestone (60 mD) with a 40 cm length and equilibrium gas was injected to the system at 18.3 MPa and 132 °C. They also modified the core holder in order to allow a

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removable lateral coating around the core. This coating was used during initial saturation of the sample and removed before gas injection, creating a fracture or a dead volume full of reservoir oil around the core. However, they did not mention about the type of lateral coating and the methodology used for the purposes. The experiments were simulated using a fully compositional single porosity simulator.

Vidal (1992) performed some gravity drainage experiments to study the drainage and reinfiltration process using two kinds of porous media: Aerolith; marketed sintered ceramic, with high porosity (35%) high permeability (close to 5 Darcy); and Vosges Sandstones with 24% porosity and 0.46 Darcy. The two fluids used were air and a neutral oil, Isopar L.

Sajjadian et al. (1999) performed laboratory studies of gravity drainage in fractured rock investigating the effect of capillary continuity and reinfiltration. Irrespective of their results, experimentation in atmospheric conditions using synthetic oil and air as test fluids was the weakness of their laboratory work. Hujun et al. (2000) investigated $CO_2$ gravity drainage in artificially fractured core using dead oil at the reservoir temperature of 58.9 °C and concluded that $CO_2$ gravity drainage could significantly enhance oil recovery after waterflooding in the naturally fractured Spraberry Trend Area. In their experiment artificial fracture was defined as the gap between two pieces of the core. Ayatollahi et al. (2005) presented gravity drainage experiments in unconsolidated sand-packed column having permeability of nearly 100 Darcy in different wetting states using synthetic oil in atmospheric condition. They concluded that residual oil saturation to gas $S_{org}$ for the oil and mixed-wet sand packs are low enough to make the process attractive for non-water-wet reservoirs.

As can be seen, the bulk of the experimental studies were performed using dead (synthetic) oil and air as test fluids in atmospheric condition which is usually not related to reservoir condition. Therefore the scarcity of experimental data and difficulty encountered in obtaining such data, have made laboratory work in reservoir conditions attractive for this process.

To clearly define the gas injection experiments, it is necessary to isolate the phase behavior effects. Equilibrium and non-equilibrium gases have different behaviors causing gravity drainage and diffusion effects during the gas oil displacement. To accomplish this, the experiments were conducted using binary fluids with the injection gas and oil in complete equilibrium so that no mass transfer would take place between the phases during the experiment. Therefore gravity drainage will be the only mechanism in this part of the study. Due to some limitation regarding the length of the sample, the cores with 20 cm in length have been chosen. Therefore, in order to overcome the threshold height of the sample, gravity drainage experiments have been performed at low interfacial tension. Actually in most of EOR projects, production is increased by decreasing IFT between fluids, and all of the production mechanisms (e.g. gravity drainage) are encountered with different values of IFT.

## 2. Fluid and rock properties

The porous medium used in all experiments was a cylindrical core sample of chalk with a length of around 20.0 cm and 3.8 cm in diameter. The porosity was 44%, and the absolute permeability to liquid, measured with $n$-heptane at the room temperature, was around 5 mD. Table 1 provides an overview of the core samples properties.

All secondary and tertiary gravity drainage tests were performed with synthetic binary mixture as live oil and equilibrated gas as gas phase. The mixture was a binary hydrocarbon with a molar composition of 75.47% with methane and 24.53% with heptane. We chose to use such a binary system of hydrocarbon fluids because the thermodynamic properties are well known. Interfacial tension between the phases (IFT), oil formation volume factor, phase densities, phase volumes at different pressures and bubble point pressure were the parameters measured experimentally.

**Table 1**
Properties of porous media.

| Exp. no. | Permeability (mD) | Porosity (%) | Length (cm) | Pore volume ($cm^3$) |
|---|---|---|---|---|
| 1 | 5.2 | 0.44 | 19.6 | 98.0 |
| 2 | 4.7 | 0.44 | 19.6 | 99.0 |
| 3 | 4.7 | 0.44 | 19.6 | 98.0 |
| 4 | 5.0 | 0.44 | 19.6 | 98.0 |

However, the published experimental data by Reamer et al. (1956) are also used to verify and predict some other parameters. These PVT data are necessary to tune the EOS model to produce the accurate and reliable results.

Constant composition expansion experiment was performed at constant temperature of 85 °C shown in Fig. 1. As it is clear the bubble point of the mixture is around 229.5 bar at 85 °C.

Phase densities and oil formation volume factor were also measured at three different pressures close to bubble point. Tables 2 and 3 summarize the properties of the system $C_1$–$nC_7$ at 85 °C.

## 3. Tuning of EOS model

Critical pressure, temperature and bubble point pressure at some certain temperature and different $C_1$ mol% are known (Reamer et al. (1956)). Regressions have been done based on available data to find the properties at desired temperature and $C_1$ mol%. The critical point and bubble point data have been simulated to obtain the critical point and bubble point at different pressures and temperatures. Results are given in Figs. 2 and 3.

Tuning of the EOS model was done using a PVT simulator. The Soave–Redlich–Kwong (SRK) equation of state (Soave, 1972) with temperature dependent Peneloux volume correction (Peneloux et al., 1982) was used as the equation of state. Five model parameters were tuned: the critical pressures and temperatures of methane and $n$-heptane and the interaction coefficient $k_{ij}$. Results for the phase behavior of the system using tuned and non-tuned EOS model are

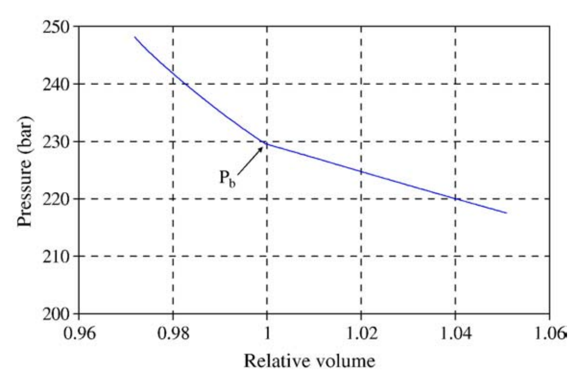


**Fig. 1.** Pressure–volume plot of mixture at 85 °C to determine its bubble point pressure.

**Table 2**
Densities, oil formation volume factors and IFT at different pressure and constant temperature (85 °C).

| Pressure (bar) | Oil density ($g/cm^3$) | Gas density ($g/cm^3$) | $B_o$ (rv/stc v) | IFT (mN/m) |
|---|---|---|---|---|
| 220 | 0.407 | 0.223 | 2.28 | 0.15 |
| 210 | 0.433 | 0.198 | 2.1 | 0.374 |
| 200 | 0.452 | 0.178 | 1.98 | 0.686 |