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Three-phase measurements of oil and gas trapping in sand packs

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ABSTRACT

We measure the trapped saturations of oil and gas as a function of initial saturation in water-wet sand packs. We start with a water-saturated column and inject octane (oil), while water and oil are produced from the bottom. Once water production has ceased, air (gas) then enters from the top, allowing oil and gas to drain under gravity for different times. Finally water is then injected from the bottom to trap both oil and gas. The columns are sliced and the fluids analyzed using gas chromatography. We find that for high initial gas saturations more gas can be trapped in the presence of oil than in a two-phase (gas/water) system. The residual gas saturation can be over 20% compared to 14% in two-phase flow [Al Mansoori SK, Iglauer S, Pentland CH, Bijeljic B, Blunt MJ. Measurements of non-wetting phase trapping applied to carbon dioxide storage. Energy Procedia 2009;1(1):3173–80]. This is unlike previous measurements on consolidated media, where the trapped gas saturation is either similar or lower to that reached in an equivalent two-phase experiment. For lower initial gas saturation, the amount of trapping follows the initial-residual trend seen in two-phase experiments. The amount of oil trapped is insensitive to initial gas saturation or the amount of gas that is trapped, again in contrast to measurements on consolidated media. More oil is trapped than would be predicted from an equivalent two-phase (oil/water) system, although the trapped saturation is never larger than the maximum reached in two-phase flow (around 11%) [Pentland CH, Al Mansoori SK, Iglauer S, Bijeljic B, Blunt MJ. Measurement of non-wetting phase trapping in sand packs. In: SPE 115697, proceedings of the SPE annual technical conference and exhibition, Denver, Colorado, USA; 21–24 September 2008]. These initially surprising results are explained in the context of oil layer stability and the competition between snap-off and piston-like advance. In two-phase systems, displacement is principally by cooperative piston-like advance with relatively little trapping, whereas in consolidated media snap-off is generally more significant. However, oil layer collapse events during three-phase waterflooding rapidly trap the oil which acts as a barrier to direct water/gas displacement, except by snap-off, leading to enhanced gas trapping.

1. Introduction

Carbon capture and storage, where carbon dioxide (CO_2) is collected from industrial sources and injected underground is one technique to mitigate atmospheric emissions of greenhouse gases [15]. It is important that the injection scheme is designed such that the CO_2 is safely stored and will not escape to the surface.

A quick and effective way to render the CO_2 immobile is through capillary trapping [3,11,15] that occurs during natural groundwater flow or at the trailing edge of a rising CO_2 plume. Several simulation studies have emphasized the importance of this mechanism for CO_2 storage [9,19,22,29,34,35]; capillary trapping can be enhanced by water injection [19] and it is possible to design injection to maximize trapping [34]. For the petroleum industry, when CO_2 is injected into oilfields, how much oil that can be recovered by gas injection is controlled by the residual oil saturation, while, again, the amount of trapped CO_2 will determine storage efficiency.

In this work, we consider CO_2 capillary trapping in aquifers and oilfields, through analogue laboratory experiments that measure residual oil and gas saturations in water-wet sand packs. We will use the terms residual saturation and trapped saturation interchangeably to refer to the minimum saturation of a non-wetting phase that is reached after displacement by a wetting phase (water).

1.1. Capillary trapping

In the literature, there is a large body of data on trapping applied to waterflooding oil and gas reservoirs; Fig. 1 shows the trapped gas saturation as a function of initial saturation during three-phase flow for consolidated porous media [4,12,16,17,21,23,28,35]. The scatter in Fig. 1 is caused by variation in interfacial

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Nomenclature

a	coefficient to relate the reduction in residual oil saturation to the trapped gas saturation
C_{trap}	trapping capacity
GC	gas chromatography/chromatograph
S	saturation
ϕ	porosity

Subscripts

g	gas
i	initial
n	non-wetting phase (oil plus gas)
o	oil
r	residual or trapped
w	water

tension (the authors used different fluid systems), pore morphology, displacement mechanism (some authors established initial and residual saturations by displacement, whereas others used evaporation and/or spontaneous imbibition which is not necessarily representative of reservoir processes), and wettability (most cores were water-wet, but also mixed-wet and oil-wet samples were investigated). We see that the trapped saturation increases approximately linearly with initial saturation before reaching a maximum that ranges between around 15% and 35%. These experiments were performed on consolidated rocks which tend to have relatively low porosity and have a wider range of pore sizes compared to the homogeneous sands we will study: as a result, the residual saturations are higher. However, as we show later, under some conditions the fraction of the overall volume occupied by trapped phase will be as high or higher than measured on consolidated rock.

Many authors have suggested that very low oil saturations can be reached during three-phase displacements [2,5–7]. In these experiments, the residual oil saturation was reached by gravity drainage, where gas displaced oil and water. If the system is spreading (i.e. the oil spreads on the surface of water in the presence of the gas), then oil layers form in the pore space, with gas occupying the center and water in the corners. These layers provide hydraulic continuity of the oil phase so that very low saturations can be reached. This observation is well established, and measurements on similar systems to ours [5,6] have shown that the residual oil saturation approaches zero as drainage continues. This analysis is relevant for gas injection, or gas gravity drainage, where gas is injected into an oil-field to displace oil and water, or where the gas cap expands; in contrast, we are interested in oil and gas trapping during waterflooding.

1.2. Three-phase residual oil saturation

Previous work [8,12,23,27,36] has shown that the residual oil saturation in three-phase flow is reduced from its two-phase value (where no trapped gas is present) according to:

$$S_{or}^{3p} = S_{or}^{2p} - aS_{gr}^{3p}, \qquad (1)$$

where a is the coefficient to relate the reduction in residual oil saturation to the trapped gas saturation, S_{gr}^{3p} is the residual gas saturation in the presence of oil and water, S_{or}^{3p} is the residual oil saturation after waterflooding in the presence of gas, and S_{or}^{2p} is the residual oil saturation after two-phase waterflood with no gas present.

It is assumed that gas and oil are both trapped in a fixed number of larger pore spaces and, in three-phase flow, compete for these spaces – hence the amount of oil or gas trapping is reduced from an equivalent two-phase (oil/water or gas/water) displacement. Water-wet data from Holmgren and Morse [12] and Kyte et al. [23] suggest that a is 0.45. Egermann et al. [8] reported similar results. Skauge [36] reported values of 0.5 to 1 for water-wet systems, while results from MacAllister et al. [27] for Baker dolomite indicated that a is 0.75; Caubit et al. [4] found $a = 0.2$. Ma and Youngren [26] showed that the residual oil saturation after tertiary waterflood in three-phase flow is lower than the residual oil saturation obtained by waterflooding, but did not quantify the value of a. Kortekass and van Poelgeest [20] confirmed similar behavior as Ma and Youngren during a waterflood following pressure depletion in a water-wet core. Fayers [10] provided a review of the literature and proposed that $a = 0.55$ for water-wet systems.

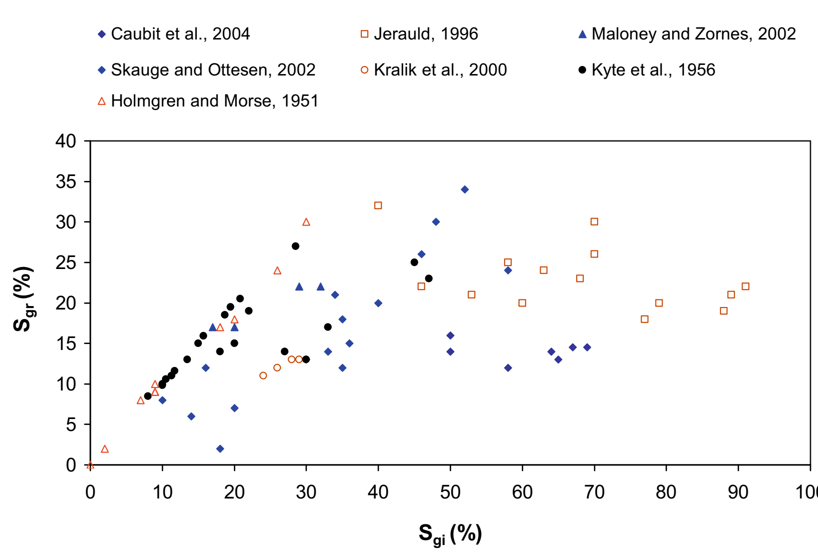

Fig. 1. Database of three-phase residual gas saturation S_{gr} versus initial gas saturations S_{gi} in the literature.