Best Paper Award: Second Honorable Mention

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GAS INJECTION AND HETEROGENEOUS WETTABILITY: WHAT IS THE RELEVANT INFORMATION THAT PETROPHYSICS CAN PROVIDE

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Abstract

The objective of the present paper is to look at the effect of small wettability heterogeneities (decimetric) on the phase distributions, recovery kinetics and sweep efficiency during a gas injection process. Secondary gas injection experiments have been performed in unconsolidated porous media of well controlled wettability: uniformly water-wet, uniformly oil-wet, and an heterogeneous sandpack consisting of two long water-wet parts separated by a 2 cm thick oil-wet stratum. 3-D saturation profiles of water, oil and gas were obtained with a dual energy CT scanner. The experiments were simulated using a reservoir simulator. In the uniform wettability cases, three-phase relative permeabilities as a function of the three fluids saturations were obtained by history matching of the recovery curves and the experimental saturation profiles. These relative permeabilities along with the corresponding capillary pressures were introduced into a simulator representing the heterogeneous structure.

Both, experiments and simulations, demonstrated that wettability heterogeneities play a major role on the global efficiency of a gas injection by drastically affecting phase distributions and displacement mechanisms. It is also shown that relative permeabilities and capillary pressures for the homogeneous structures properly incorporated into a reservoir model, taking into account the geometric characteristics of the heterogeneity, describe very satisfactorily oil recovery and fluid distribution in the heterogeneous porous medium.

Introduction

It has been already demonstrated that in order to analyse and describe gas injection processes the rock/fluid interactions have to be properly taken into account[1-6]. This is a difficult task because in many cases of practical interest the porous medium wettability is far from being uniform. In fact wettability heterogeneities may appear at different scales within the reservoir, from the microscale to the macroscale. They may also be related to permeability heterogeneities. Permeability heterogeneity plays a determining role as it has been shown in former studies[7].

Determination and measurement of the relevant parameters for core analysis purposes when wettability heterogeneities are involved is of prime interest. Achieving this through a careful analysis of experimental and simulation results constitutes the ultimate goal of this work. In the present paper the effect of small wettability heterogeneities (decimetric) on the phase distributions, recovery kinetics and sweep efficiency during a gas injection process is studied. To this end gas injection experiments at irreducible water saturation in homogeneous and heterogeneous wettability sandpacks have been performed, and simulations have been realised using a reservoir simulator.

The paper consists of two parts. The first part is devoted to the experimental study of gravity assisted gas injection process in homogeneous and heterogeneous wettability structures. Recovery kinetics and saturation profiles are compared and interpreted. The second part concerns the numerical modelling of the experiments. Three-phase relative permeabilities as functions of the three fluids saturations for the uniform wettability cases are obtained by history matching of the recovery curves and the experimentally obtained saturation profiles. Capillary pressure curves, obtained by centrifuging homogeneous small sandpacks, similar to the large ones used in the gas injection experiments, are used as input in the simulations. Then the heterogeneous case is analysed. The heterogeneous structure is properly represented in the simulator, and data for the uniform parts (K_r, P_c) are used as input.

The results provide sufficient evidence of the fact that heterogeneous wettability dramatically affects the macroscopic characteristics and transport properties of a gas injection process. They also prove that complete and high quality measurements in the uniform wettability segments constitute the corner stone of an efficient analysis and prediction of gas injection in heterogeneous structures.

Results and Discussion

Gas injection experiments in homogeneous and heterogeneous structures

Porous media - Gravity assisted gas injection experiments have been performed, at laboratory conditions, in unconsolidated porous media (sandpacks with average grain size of 120mm) of well controlled wettability: uniformly water-wet, uniformly oil-wet, and an heterogeneous sandpack consisting of two long water-wet parts separated by a 2 cm thick oil-wet stratum. The average porosity was 0.35 and the absolute permeability of the order of 10D. All three sandpacks were 5cm in diameter and around 50cm in length. The porous medium characteristics for each experiment are given in Table 1.

TABLE 1: PETROPHYSICAL PROPERTIES AND RECOVERY DATA

Exp .No	Wettability	f	K (mm^2)	S_{wi}	S_{org}	Recovery % OOIP
1	water-wet	0.348	11	0.166	0.11	86.8
2	oil-wet	0.334	9.5	0.166	0.21	74.8
3	heterogeneous	0.341	13.1	0.24	0.24	67.6

Water-wet conditions were obtained by thoroughly cleaning and rinsing the sand. Strongly oil-wet conditions were obtained by silylating the sand. This procedure does not affect grain size distribution, and, as microscopically observed, the grain surface does not change either.

Fluids - The fluid system used consists of brine (NaCl 30g/l), Soltrol 170 (colored with oil-red) and air. Densities (r_o, r_w), viscosities (m_o, m_w) and surface and interfacial tensions (g_{wg}, g_{og}, g_{ow}) are given in Table 2. The system has a positive spreading coefficient ($S_{o/w}$=g_{wg}-g_{ow}-g_{og}).

TABLE 2. PHYSICOCHEMICAL PROPERTIES OF THE FLUID SYSTEM

Fluid system	r_w Kg/m^3	r_o Kg/m^3	m_w c p	m_o c p	g_{wg} mN/m	g_{og} mN/m	g_{ow} mN/m	$S_{o/w}$ mN/m
Brine (30g/l NaCl)-Soltrol 170-	1019.	774.	1.05	2.75	70.	26.5	35.	+8.5

Experimental procedure - The experimental procedure, which is the same in homogeneous and heterogeneous structures, can be summarized as follows:

1. Water is introduced under vacuum in the dry and vertically positioned sandpack to fully saturate it. The porosity profile is measured by CT-scanner. The end point of the oil relative permeability curve ($K_{ro, max}$) is also measured.
2. The water is displaced by oil down to irreducible water saturation, S_{wi}. The water/oil saturation profiles are determined by CT-scanner.
3. The outlet valve is connected to the collection vessel. A differential pressure DP=16mbar is applied along the core. Both inlet and outlet valves are opened. The weight of the oil recovered is registered as a function of time.
4. At the end of the experiment the average residual oil saturation, S_{org}, is calculated and the saturation profiles of the three fluids are determined with a dual energy CT-scanner.

Recovery kinetics - Recovery data for all three experiments are given in Table 1, and the oil recovery curves in Figure 1. The characteristics of the oil recovery in the homogeneous wettability porous media have already been discussed elsewhere(6). It is observed that the recovery as a function of time is always higher in water-wet porous media than in oil-wet ones. This is due to the fact that, in the latter, water being the non-wetting phase occupies the large pores thus lowering the permeability to oil. At the late stages the recovery curve in water-wet porous media brings the signature of flow of oil through spreading films: long and slow recovery leading to very low residual oil saturations (S_{org}=11%). In oil-wet porous media, where capillary retention is high, much lower oil recoveries are obtained

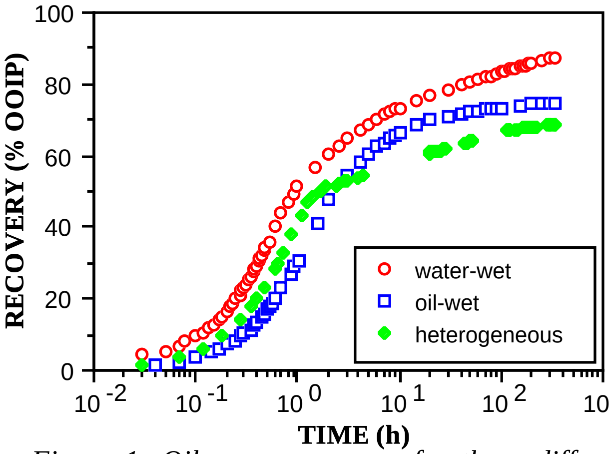

Figure 1: Oil recovery curves for three different core wettabilities.

(S_{org}=21%). In the heterogeneous sandpack the oil recovery curve is initially situated between the water-wet and the oil-wet curve reflecting the effect of the presence of the oil-wet stratum, where, as explained, the permeability to oil is reduced. Then it resembles to the curve in the water-wet medium: it presents the long recovery queue, fingerprint of flow of oil through spreading films. However it remains below both the water-wet and the oil-wet recovery curves. As a result the efficiency in the heterogeneous sandpack is poorer than in both other cases (S_{org}=24%).

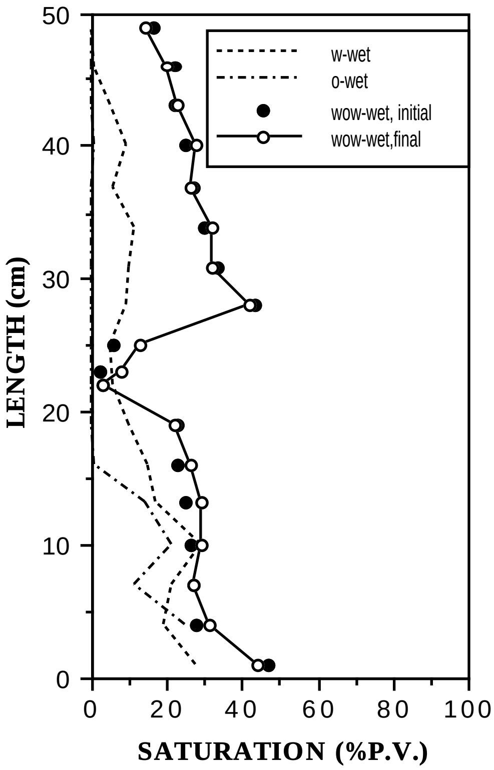

Figure 2: Irreducible water saturation profiles in the homogeneous and heterogeneous cores.

Fluid distributions - At this stage valuable information and hints for interpretation can be provided by the saturation profiles in the three different media. In Figure 2 the initial and final (before and after gas injection) water saturation profiles in the heterogeneous core are presented. For comparison the final water saturation profiles in the homogeneous cores are also given. The effect of the presence of the oil-wet stratum between the two water-wet parts is clearly seen. The discussion that follows concerns mainly the displacement mechanisms and fluid distributions in the heterogeneous core, the homogeneous cases have been commented elsewhere[6].

In establishing the irreducible water saturation, the displacement of water by oil takes place from the top to the bottom of the core. During this drainage, and as the average oil saturation increases, capillary pressure builds-up. When the oil reaches the oil-wet layer, the displacement mechanism turns to imbibition. The oil-water capillary pressure curve takes negative values. Oil moves spontaneously in the oil-wet region and the pressure decreases. The water saturations in the oil-wet layer are extremely low, and water looses its hydraulic continuity within it. Thus the water in the upper water-wet part gets trapped and it is distributed in a way respecting the capillary retention profile for uniformly water-wet porous media.

In their way towards the bottom of the core the oil-water interfaces meet the second oil-wet/water-wet boundary. Then the displacement mechanism becomes drainage and pressure builds-up again. When the pressure threshold value is attained, oil invades the lower water-wet part, and the saturation profile reflects the water capillary retention within it.

It is evident that before gas injection oil is the only continuous phase. Thus when gas is injected in the porous medium from the top, the dominant displacement mechanism is oil drainage. Water is practically not affected by the presence of gas, and very little accumulation toward the porous medium bottom is observed (Figure 2).

To interpret the final oil and gas saturation profiles (Figures 3 & 4), the capillary pressure curves in the different parts of the porous medium are needed. Gas-oil capillary pressure in presence of irreducible water has been measured by centrifuge experiments performed in small sandpacks similar to the large porous media. Uniformly water-wet and oil-wet porous media have been examined. Detailed description of these experiments is provided elsewhere(3). In Figure 5 the dimensionless capillary pressure $(P_c/\gamma)\sqrt{K/\phi}$ is plotted as function of the gas saturation.

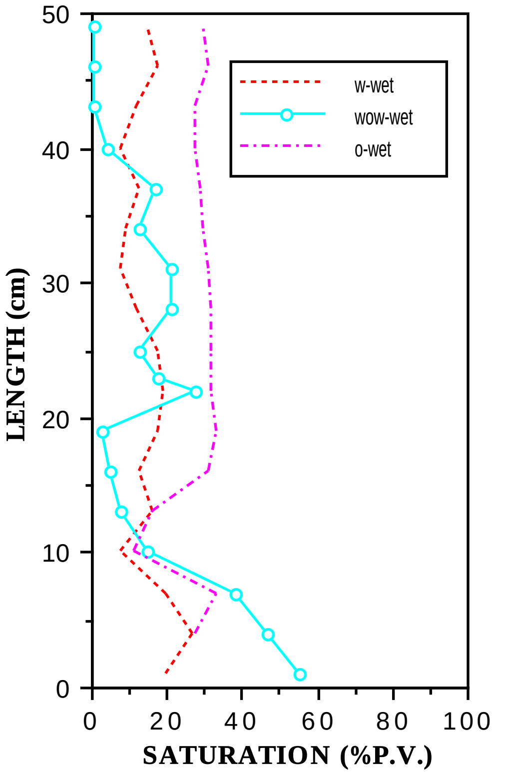

Figure 3: Final oil saturation profiles in the homogeneous and heterogeneous cores.

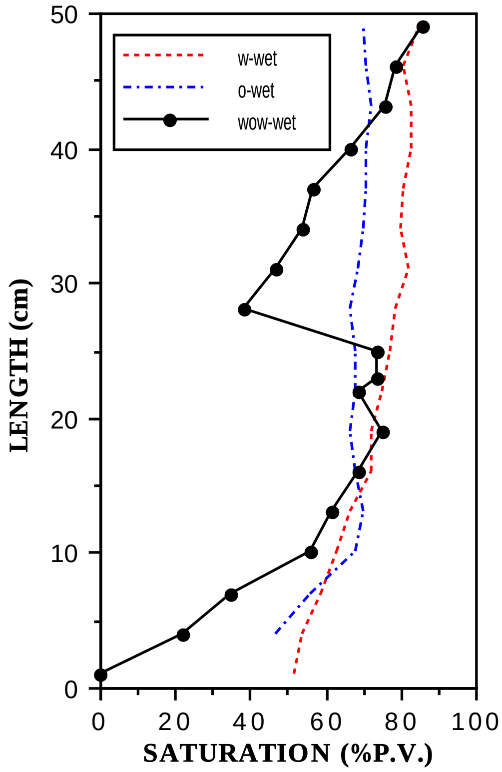

Figure 4: Final gas saturation profiles in the homogeneous and heterogeneous cores.

As gas invades the upper water-wet part, the pressure increases and a wetting phase (water+oil) retention profile is built up. Capillary continuity in the upper water-wet/oil-wet boundary explains the saturation discontinuity. In the oil-wet layer this pressure level corresponds to very low oil saturations which are in the limit of the oil hydraulic continuity. Very rapidly oil relative permeabilities in the oil-wet layer become so low, due

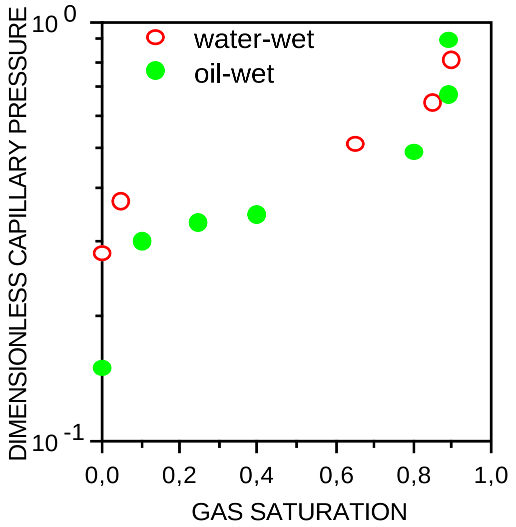

Figure 5: Oil-gas capillary pressure in water-wet and oil-wet porous media at irreducible water conditions.

to high capillary retention, that the oil in the upper water-wet part is practically trapped. With the oil being thus discontinuous, gas continues the displacement in the lower part of the core where a new capillary profile is established. The fact that the oil recovery curve for sufficiently long drainage times resembles to the water-wet curve, but with much lower global oil recovery, is now easily explained: the curve brings the signature of oil drainage in water-wet medium under spreading conditions, but only the lower water-wet part produces, the upper being isolated by a non-conducting layer. In fact the oil-wet layer behaves like a fracture with the particularity that it has a non-zero capillary pressure and the wetting phases attain rapidly their irreducible saturations (non-continuous).

Numerical simulations

The above described experiments have been simulated using a reservoir simulator (ATHOS^R), and the corresponding relative permeability curves have been obtained by history matching the recovery curves and the final saturation profiles. ATHOS^R is a multipurpose compositional reservoir simulator based on a three-phase and 3-D model. Both classical (Stone's models) relative permeabilities and three-phase relative permeability tables (K_r depending on two saturations) can be introduced as input in the simulator.

Simulations were carried out in both homogeneous and heterogeneous wettability cores. As it will be demonstrated here, the influence of wettability heterogeneity, which can be very significant, is properly captured by the simulations. The purpose of the simulation studies in homogeneous porous media was to identify the relative permeabilities to be used as input in the heterogeneous core simulations and to compare the different permeability models. In the heterogeneous core the objective was to take into account the influence of an oil-wet zone between two water-wet parts on the oil recovery and fluid distributions starting with data in the homogeneous facies. For the simulations, 20 cells were considered in the vertical direction. The simulations were very little CPU time consuming. 20 to 30s on SUN^R, Ultra 1, were required to simulate a 20 days experiment.

Homogeneous case - The simulations in homogeneous media are considered first. The simulation starts with a given profile of irreducible water corresponding to the experimentally measured distribution. The history matching in both water-wet and oil-wet porous media was based on the fitting of the oil recovery curve through an iteration/correction method; however, the agreement between experimental and simulated saturation profiles was also systematically controlled, since it is considered that only fitting of oil production and fluids distributions guarantees that the identified relative permeabilities constitute a solution of the problem. The oil and gas relative permeabilities thus identified in uniformly water-wet and oil-wet porous media are presented in Figure 6 and the comparison between simulated and experimental production curves in Figure 7.

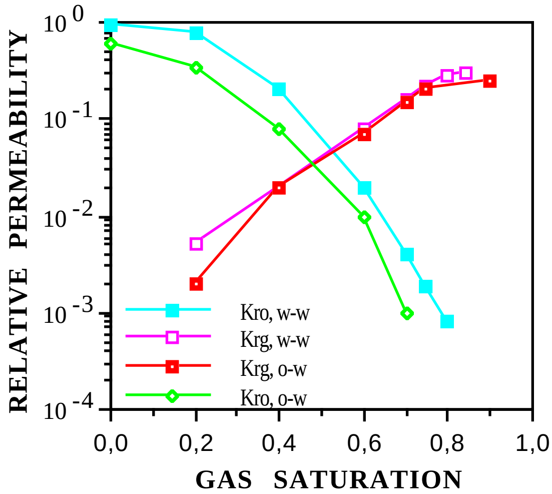

Figure 6: Gas and oil relative permeabilities in uniform wettability cores.

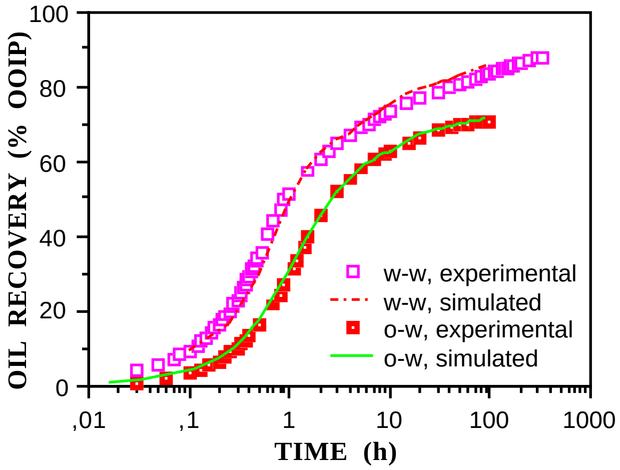

Figure 7: Experimental and simulated recovery curves in uniform wettability porous media.

The three-phase relative permeabilities used in the simulations are either calculated from two-phase data applying Stone's model or directly introduced in form of tables as functions of two saturations. A comparison can be attempted between the Stone's model and three-phase relative permeabilities functions of two saturations, since in this domain Stone's model assumptions are still valid. Simulated and measured S_g profiles are given in Figure 8. The influence of Stone's model can only be noticed at the top of the core. A linear relationship between S_{om} (residual oil saturation to simultaneous displacement by gas and water) and S_g (gas saturation) has been chosen here. With a quadratic dependence of S_{om} on S_g(8), the result remains the same.

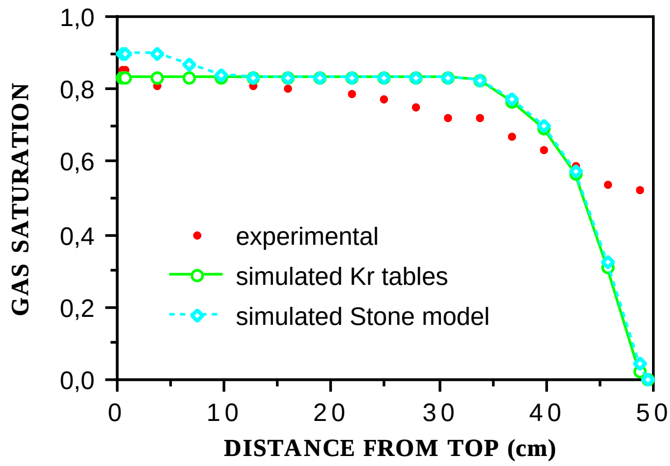

Figure 8. Comparison of experimental and simulated final gas saturation profiles (at 20 days) in uniformly water-wet porous medium. The simulations were performed with relative permeability tables and with the Stone I model (taking a linear relationship between S_{om} and S_g).

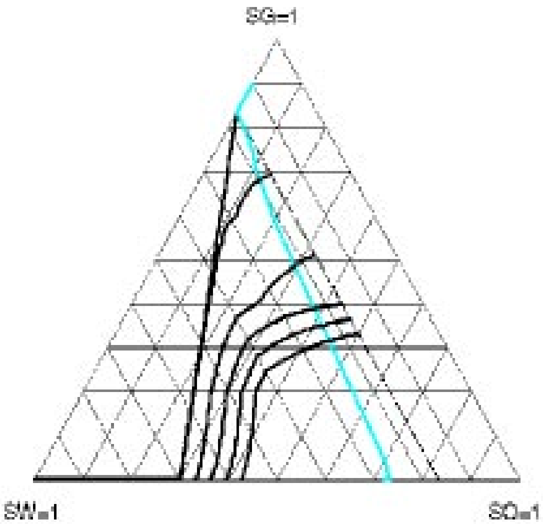

Figure 9: Oil isoperms (dark lines) evaluated with Stone I model, and the saturation trajectory (grey line) for gas injection in the water-wet porous medium.

This is due to the saturation path followed within the saturation triangle (Figure 9); only the flat part of the isoperms is described. The deviations between experimental and simulated profiles at the bottom of the core are due to extremity effects. In these regions the measured saturation values are frequently subject to important experimental error.

Heterogeneous case - With all the information acquired in homogeneous wettability cores, simulations have been performed for heterogeneous wettability conditions. Only tabulated relative permeabilities have been used (the ones identified for the homogeneous cores) since Stone's assumptions do not hold anymore.

The comparison between experimental and simulated recovery curve in the heterogeneous core is given in Figure 10. Figure 11 shows the comparison between experimental and simulated final gas saturation profiles, and the predicted evolution of the gas distribution with time. First important observation is the quite good agreement between experiment and simulation. The influence of the oil-wet region is described by the simulation in a very satisfactory way.

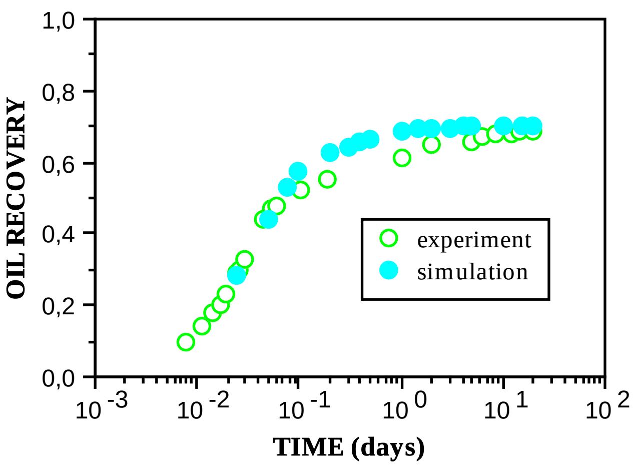

Figure 10: Experimental and simulated recovery curves for the heterogeneous core.

The other important information concerns the kinetics of oil recovery in the heterogeneous medium; it is deduced from Figure 11 that oil in the upper water-wet part gets rapidly stranded and practically only the lower water-wet part keeps producing for a long time. This observation confirms the interpretation advanced in the experimental part to explain the low global recovery in the heterogeneous structure. In Figure 12 the influence of absence of capillary pressure in the heterogeneous core simulation is demonstrated; the flat gas saturation profile does not at all correspond to the experimental reality, and total recoveries are not well described either. This result shows clearly that in order to correctly interpret displacements in heterogeneous wettability cores it is absolutely necessary to take properly the capillary pressure into account.

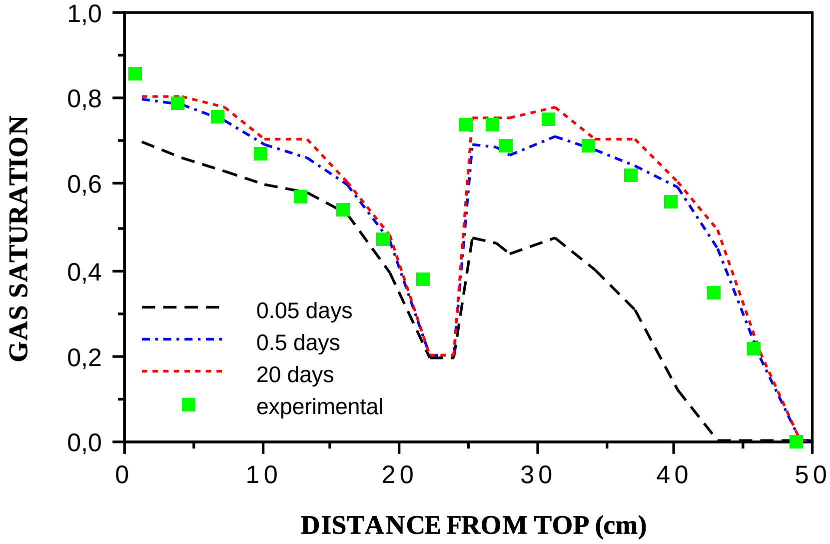

Figure 11. Comparison between simulated gas saturation profiles at different times and final experimentally obtained profile (heterogeneous case)

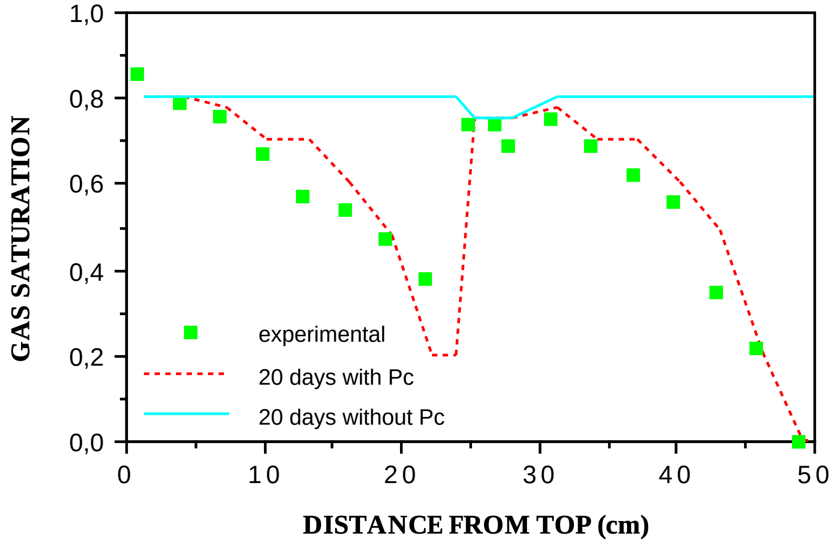

Figure 12. Influence of capillary pressure on simulated gas saturation profile (heterogeneous case) and comparison with the experimental results.

Conclusions

Secondary gravity assisted gas injection experiments have been performed in unconsolidated porous media of well controlled wettability: uniformly water-wet, uniformly oil-wet (silylated sand), and an heterogeneous sandpack consisting of two long water-wet parts separated by an oil-wet layer. The experiments, both in homogeneous and heterogeneous porous media, were simulated using a reservoir simulator.

Capillary pressure curves, obtained by centrifuging homogeneous small sandpacks similar to the large ones used in the gas injection experiments, were used as input to the simulator. Three-phase relative permeabilities as a function of the three fluids saturations for the uniform wettability cases were obtained by history matching of the recovery curves and the experimental saturation profiles. They were introduced, along with the corresponding capillary pressures, into a simulator representing the heterogeneous structure; calculated oil recovery curves and saturation profiles were compared to experimental ones.

Both, experiments and simulations, demonstrated that wettability heterogeneities play a major role on the global efficiency of a gas injection, by drastically affecting phase distributions and displacement mechanisms. More specifically:

1. High capillary retention, mainly in the water-wet parts isolated by oil-wet layers, leads to poor sweep efficiency in the heterogeneous porous medium.
2. Saturation profiles and oil recovery curve in the heterogeneous porous medium are nicely described by using relative permeabilities and capillary pressures for the homogeneous structures properly incorporated into a reservoir model taking into account the geometric characteristics of the heterogeneity.
3. Interpretation of gas injection experiments when heterogeneous wettability is involved necessitates a careful analysis of the displacement mechanisms and acquisition of high quality data on the homogeneous parts.

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