Abstract - The objective of the present work is to study the effect of wettability heterogeneities on:
(1) displacement mechanisms, (2) sweep efficiency, and (3) trapped oil quantities and fluid distribution in three-phase gas injection.

To this end an experimental investigation is performed and a theoretical simulator developed. Secondary gas injection experiments are conducted in transparent glass micromodels of heterogeneous wettability. Oil-wet patches in a water-wet matrix are obtained by selective silane grafting on the glass surface. Different heterogeneity patterns are considered for the same oil-wet over water-wet surface ratio. Displacement sequences are video-recorded and fluid saturations are determined by image analysis.

A theoretical model of three-phase flow in a porous structure is also developed. In this model the porous medium is simulated as a network of interconnected pores. The model permits to impose a heterogeneous wettability by assigning different water/oil contact angles according to the desired wettability pattern. The calculation of flow within the network is taking into account the flow of oil through wetting and spreading films and the displacement mechanisms observed in the transparent micromodels.

Comparison between experimental results and simulations shows that the size and distribution of wettability heterogeneities strongly affect the microscopic and macroscopic behaviour during a gas injection.

1. Introduction

Gas injection processes occupy an important place among improved oil recovery methods. In such processes three phases (water, oil, gas) coexist within the porous matrix. The wettability determines the ability of one liquid to spread over a solid and to form wetting films, while the spreading energy controls the ability of a liquid to spread on another liquid and to form spreading films. The thickness and stability of both wetting and spreading films affect the hydraulic continuity of the aqueous and the oleic phase, and consequently the displacement mechanisms and efficiency. It has been already proved that the wettability characteristics of the solid surface and the spreading characteristics of the fluid system hold the key roles when three phases flow simultaneously in a porous medium1,2,3.

For a long time and for simplicity reasons oil reservoirs were considered uniformly water-wet. Nowadays it is admitted that heterogeneous wettability is very frequent and that different scales of heterogeneity may exist within the reservoir, from the microscale to the macroscale. These heterogeneities may also be related to permeability heterogeneities which are known to play a determining role on the flow properties. Non-uniform wettability may be due to the adhesion of organic components of crude oil to the solid surface, or in the presence of naturally oil-wet minerals within the rock4. Two-phase flow in heterogeneous wettability media has been studied with emphasis on the flow of oil through wetting films on the grain surface5, and modelling aspects have already been looked at6. It is generally recognised that different types of wettability can result in wide variations in the residual oil saturations after waterflooding, directly related to the possibility for the oil to maintain its hydraulic continuity by flowing through connected oil-wet paths. However very little has been done on the effect of wettability heterogeneities during a water/oil/gas displacement in the porous medium. Recent studies at the core scale have proven that heterogeneous wettability dramatically affects the macroscopic characteristics and transport properties of a gas injection process7.

The objective of the present paper is to analyse the effect of wettability heterogeneities on the sweep efficiency of a gas injection by looking at the microscopic displacement mechanisms in three-phase
flow when heterogeneities are involved. First the laboratory experiments in transparent micromodels of heterogeneous wettability are described. Then the main concepts and flow rules in the network simulator are summarised. Finally the numerical and laboratory experiments are compared in terms of trapped oil quantities and fluids distribution.

2. Experimental study

Network micromodel / Fluid system - The model porous medium used in the experiments is a network of the chamber-and-throat type, constructed from glass plates using a lithographic method. The network parameters (planar porosity, coordination number, chamber and throat size distributions) can be adjusted to the desired values. The network used is a square lattice with node-to-node distance of 1200µm, a chamber to throat aspect ratio of 5:1, and a planar porosity of 0.4.

The micromodels consist of two optically flat glass plates with the network pattern etched on one of the plates and the inlet/outlet holes drilled in the other plate. Wettability heterogeneities according to the desired pattern are created in a symmetric way on both plates using a silylating technique. This technique consists in depositing a thin film of silane (octadecyltrichlorosilane) on the glass surface. The original water-wet character of the plates can be re-established by cleaning them with chromosulfuric acid. After preparation the plates are joined face-to-face, sealed (a vacuum between them is achieved) and placed into a pressure bath with two viewing windows. Then an overburden pressure of 2bars is applied in the bath liquid (an aqueous solution of glycerol to obtain the same refractive index as the glass).

The experiments were performed in ambient conditions. The following fluid system is used in the experiments: n-dodecane with Oil Red / deionized water / nitrogen. The fluids were very carefully chosen and prepared. Their densities (ρ_o = 749kg.m^{-3}, ρ_w = 998kg.m^{-3}), viscosities (µ_o = 1.35cP, µ_w = 1.00cP) and surface and interfacial tensions (γ_ow = 71.2mN.m^{-1}, γ_{og} = 25.1mN.m^{-1}, γ_{wg} = 42.1mN.m^{-1}), are measured by standard techniques. The spreading coefficient obtained S = γ_{wg} - γ_{og} - γ_{ow} = +4.0, is positive. We assume that oil forms films on water in the presence of gas.

Experimental procedure - The network is first saturated with water. Then the oil is injected at a sufficiently high rate in order to attain irreducible water saturation (S_{wir}). The displacement process is videotaped and when the steady-state is achieved the network is photographed with a still camera. Then gas is injected at different pressure levels. Again the displacement is videotaped and when no more interface motion is observed a picture is taken.

After each experiment the model is cleaned thoroughly with water, isopropyl alcohol and chromosulfuric acid followed by deionized water, and finally it is dried. Saturations and fluid distributions for the three fluids in place are measured by image analysis on the still photographs. The results of this analysis are here presented as residual oil saturation to gas injection (S_{org}) and oil recovery.

Three different wettabilities have been investigated: uniformly water-wet network, heterogeneous with an oil-wet stripe parallel to flow and heterogeneous with oil-wet square patches in a water-wet matrix. For the two different heterogeneity patterns the same oil-wet over water-wet surface ratio has been applied (1:2). In each experiment three pressure levels have been investigated. At the beginning of the gas injection the gas pressure has been set to 60mbars, then when equilibrium was achieved the pressure was increased to 100mbars and finally to 185mbars.

In Figure 1 a comparison is shown between the different wettabilities at two stages of the experiment: at irreducible water saturation and at residual oil saturation to gas injection for ΔP=60mbars. It is seen that irreducible water remains immobile during gas injection in all three wettability cases. However its distribution is very different from one case to another. In the homogeneous porous medium water is almost uniformly distributed and occupies mainly small constrictions difficult for the oil to reach. In the case of the oil-wet stripe water occupies the large pores in the oil-wet region and the network outlet in the water-wet regions trapped by capillary forces. In the case of oil-wet squares water is trapped in the water-wet matrix upstream of the heterogeneities.

When gas is injected the displacement mechanism is drainage everywhere. Gas chooses the path of the least resistance to the flow, and irreducible water distribution determines the way the gas injection evolves. As it can be seen in figure 1 at low applied pressure (ΔP=60mbars) a typical drainage pattern is obtained in the water-wet micromodel. Important fingering is observed (due to unfavorable viscosity ratio) and a large oil quantity is trapped. In presence of the oil-wet stripe things are even worse. Gas preferentially invades the continuous from the inlet to the outlet oil-wet pathway, and only at the late displacment stages it starts expanding laterally toward the water-wet region. As a result the residual oil saturation is low only in the oil-wet region and the sweep efficiency is globally deteriorated. When the heterogeneity is in form of isolated squares the upstream accumulated water
inhibits the gas from readily invading the oil-wet regions. Microfingering is reduced and the water-wet regions are satisfactorily swept. Gas invades the squares laterally, and globally the best efficiency is attained.

Image analysis permits to quantify these observations as it can be seen in figures 2 and 3, where the oil saturation and recovery are plotted as functions of the applied pressure in the three different micromodels. Values corresponding to the homogeneous regions and averages over the whole network are presented. It is seen that the differences are only slightly attenuated with increasing pressure.

3. Network Modelling

Different methodologies have been developed to study immiscible microdisplacement in networks simulating a porous medium. The main models for drainage and imbibition in two-phase flow conditions are reviewed by Dullien. In the three-phase flow domain the existing network models are by far less numerous. In the present work the pore space of the permeable medium is simulated as a network of unit cells of the constricted tube type. Each unit cell has a long throat of triangular cross-section characterised by its equivalent diameter \( d \) in the range 10 to 20 \( \mu \text{m} \) and its length \( l \), and represents the main resistance to the flow. The pores are assumed to have an octagonal cross-section, with an equivalent diameter \( D \) in the range 25 to 85 \( \mu \text{m} \). The particular network model presented in this work is a 30x10 two-dimensional network, square lattice type, with a fixed periodicity length of 100 \( \mu \text{m} \), and a porosity of 0.2. The pore and throat size distributions used in this paper are typical of sandstones. Periodic boundary conditions are used in the directions perpendicular to the inlet/outlet direction, to minimise finite size effects in the results.

Solution of the flow in the network - The network model used an electrical analog to calculate immiscible displacements: the hydraulic conductivity of each unit cell is expressed as a function of the hydraulic conductivity of each phase present in the considered cell. Fluid displacements are simulated by applying a macroscopic pressure gradient across the network. Under creeping flow conditions the relationship between pressure drop and fluid flux in the network is linear. The flowrate between pore \( i \) and neighboring pore \( j \) is defined as: \( g_{ij} = g_{ij} (P_i - P_j) \), where \( g_{ij} \) is the total conductance in the throat and \( P_c \) is the capillary pressure if a meniscus is present in the throat. The capillary pressure across an interface is defined using Young-Laplace equation: \( P_c = \gamma C \), where \( \gamma \) is the interfacial tension and \( C \) is the curvature of the interface for a perfectly wetting liquid in a triangular tube. The conductance of a phase \( \alpha \) saturating a throat or occupying the center of the throat (non-wetting phase) is given by Poiseuille's law:

\[
g = \frac{\pi r_{\text{eff}}^4}{8 \mu_{\alpha} l} \text{ with } r_{\text{eff}} = \sqrt{\frac{A_\alpha}{\pi}} \text{, where } A_\alpha \text{ is the cross-sectional area occupied by phase } \alpha.
\]

In the presence of a meniscus between two phases \( \alpha \) and \( \beta \) in a throat, the conductance of the throat is the harmonic mean of the conductances of each phase.

Assuming quasi steady state, the problem for a certain flow situation is reduced to a system of linear algebraic equations, the solution of which gives us the pressure of the phase occupying the center of the pores. The pressures in the other phase forming layers in the corners of the pore space, are determined by solving a new set of equation for the considered phase. The conductance of the wetting phase or the intermediate phase \( \beta \), in the corners of a throat is approximated by an expression from Ransohoff and Radke:

\[
g = \frac{A_\beta r^2}{R_f \mu_\beta}, \text{ where } A_\beta \text{ is the cross-sectional area occupied by the phase } \beta, r \text{ is the radius of the interface and } R_f \text{ is a dimensionless resistance factor, depending on the boundary condition applied at the fluid/fluid interface, the corner geometry, the contact angle (assumed to be 0° for the wetting phase on the solid, and for the intermediate phase on the wetting phase).}
\]

The viscosity of the gas (nitrogen) is much lower than the viscosities of oil and water, and for the purpose of the simulations the gas is considered to be inviscid: consequently, the pressure in the gas is everywhere constant and equal to the entry pressure.

Simulated displacements - The initial distribution of oil (intermediate fluid in water-wet region, wetting fluid in oil-wet region) and water (wetting fluid in water-wet region) were established by simulating a two-phase displacement, which corresponds to a drainage in the water-wet regions and to an imbibition in the oil-wet regions. Then when gas is injected drainage mechanisms are applied in the water- and oil-wet regions. Oil is assumed to form wetting films in the oil-wet regions and spreading films on water in the water-wet regions. Simulations have been performed in a uniformly
water-wet network and in a heterogeneous network with the oil stripe between two water-wet regions.

The following results are obtained at the end of the two-phase (oil-water) and three-phase (gas-oil in presence of immobile water) displacement. The water distribution differs drastically from one case to the other (fig. 4a). In the water-wet network water is uniformly distributed and occupies mainly the throats. In the heterogeneous network imbibition occurred in the oil-wet stripe, trapping water in some pores, whereas water drained more slowly in the water-wet matrix, so that at oil breakthrough an important saturation of water remains at the outlet. It is seen that qualitatively these results agree rather well with the experimental observations. The continuous oil-wet stripe provides to the gas a preferential pathway easy to invade, while in the water-wet regions the sweep efficiency is less important (fig 4b). In the water-wet network, important fingering trapped a large oil quantity. With increasing pressure (fig. 4c), gas starts expanding laterally toward the water-wet matrix in the heterogeneous case. Trapped oil is slowly drained through spreading films in the water-wet network, and through wetting and spreading films in the heterogeneous network.

More work on the network simulator to incorporate all the important displacement mechanisms in order to improve agreement with the experiments is presently in progress.

4. Conclusions

In this work a first study of the effect of wettability heterogeneities in three-phase gas injection is presented, and the preliminary results are described. Experiments have been performed in original transparent micromodels with the desired wettability heterogeneity. A network simulator has been developed that takes into account drainage / imbibition mechanisms and flow through films.

The results show that:
• The trapped oil quantity depends on the type of heterogeneity for any level of applied pressure.
• Gas invades the pathways of least resistance, most of the times in the oil-wet regions, since in the water-wet ones water bridges drastically increase the resistance to flow.
• Distribution of the irreducible water depends on the type of heterogeneity and plays a major role on the displacement patterns of gas injection.

More work is needed to quantitatively describe with network simulations the effects encountered when wettability heterogeneities are involved.

References
7. Vizika, O., Duquerroix, J.P., 1997 "Gas Injection and Heterogeneous Wettability: what is the relevant information that petrophysics can provide", to be presented to the 1997 International Symposium of the Society of Core Analysts, Calgary, Canada, September 7-10
Fig.1: Phase distribution in glass micromodels with different wettability patterns.
1 - at irreducible water saturation (after oil injection).
2 - at residual oil saturation (after gas injection at $\Delta P = 60$ mbar).

a - uniformly water-wet

b - oil wet stripe parallel to flow

c - oil wet squares
Fig. 2: Residual oil saturation in micromodels with 3 different wettability patterns as function of the applied pressure.

Fig. 3: Oil recovery in micromodels with 3 different wettability patterns as function of the applied pressure.

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<tr>
<th>Uniformly water-wet</th>
<th>Oil-wet stripe parallel to flow</th>
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<td>a) Initial phase distribution</td>
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<td>$S_{wi} = 5.6%$</td>
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<tr>
<td>$S_{wi} = 32.6%$</td>
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<td>b) Residual oil saturation to gas injection at $\Delta P=300\text{mbars}$</td>
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<td>$S_{\text{org}} = 42%$; oil recovery=$56%$</td>
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<td>$S_{\text{org}} = 37.4%$; oil recovery=$42%$</td>
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<td>c) Residual oil saturation to gas injection at $\Delta P=700\text{mbars}$</td>
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<td>$S_{\text{org}} = 34.8%$; oil recovery=$63%$</td>
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<td>$S_{\text{org}} = 29.4%$; oil recovery=$56%$</td>
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Fig. 4: Comparison between phase distribution computed for two different wettabilities at three stages of the gas injection: at irreducible water saturation (a), at residual oil saturation to gas injection for $\Delta P=300\text{mbars}$ (b), and $\Delta P=700\text{mbars}$ (c). Oil is in black, irreducible water in dark grey, and gas in light grey.