TWO DIMENSIONAL IMAGING OF VISCOUS AND CAPILLARY EFFECTS IN A DIPPING STRATIFIED HETEROGENEOUS MEDIA

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ABSTRACT

This paper presents experimental results on flow of two immiscible fluids in a heterogeneous medium consisting of three blocks of porous rocks connected at a layer angle of 45 degrees.

The central block was made of Aerolith-10, an artificial sintered porous medium of high porosity and permeability, while the the two other blocks were made up of Vosges sandstone in order to have a high permeability contrast and therefore a high capillary contrast between the strata. The physical properties (porosities, permeabilities, capillary pressures, end-point saturations) of the blocks composing the heterogeneous media were measured independently on isolated samples. Both media were found water-wet.

Drainage and waterflood experiments were performed in the heterogeneous medium. Two-dimensional saturation fields were obtained by the use of a gamma-ray attenuation apparatus.

The system was first driven to immobile water saturation by a high rate oilflood. During the following non-flow period of 65 hours, the fluids reached capillary equilibrium and a significant redistribution under capillary forces of the fluids was recorded, we observed a decrease of water saturation in the high permeability layer.

The two-dimensional saturation fields recorded during the low-rate waterflood showed a significant difference in behaviour in the different layers due to the contrast of physical properties (permeability and capillary pressure). The flow is the result of the competition between the viscous and capillary forces. For this low flow-rate, the viscous effect in the high permeability layer is comparable to the capillary effect in the low permeability media.

It is concluded that two-dimensional local saturation information in larger scale three dimensional slabs of porous rocks significantly improves the interpretation of the recovery mechanisms in heterogeneous porous media.

INTRODUCTION

Two-phase flow in natural porous media is a problem of central importance in reservoir engineering and core analysis, due to the complex structure of the rocks. Several kinds of heterogeneties can be found in reservoirs. Nevertheless, the layered texture, associated to sedimentation process, seems to be the most common type.

Several studies have been performed in the field of two-phase flow in heterogeneous systems. The goal of these studies is two-fold.

* Understanding the flow behaviour of immiscible fluids in heterogeneous configuration. Due to the non linearity of the equations, these behaviours are highly complex.
* Determine averaged values ("pseudo functions") for use in numerical simulations. A review of these techniques is available in Ahmadi et al. (1993).

There is an extensive literature on heterogeneities at the reservoir scale. Core laboratory experiments are often interpreted assuming that heterogeneity effects are negligible. However, recent experimental studies have shown that this is not necessarily a correct assumption.

Layered media with flow parallel to the strata have been studied among others by Ahmed et al. (1988) and Bertin et al. (1990). In the latter paper the experiments were interpreted using the Large-Scale Averaging Method (Quintard and Whitaker, 1988). Some papers are available also in the case of flow normal to the strata (Hinkley et al.; 1986, Graue et al.; 1990, Graue; 1994, Laribi et al.; 1994). The case of nodular media, or porous media with lenses, has been studied by Alhanai et al. (1992) and Dawe et al. (1992). Recently a study by Roti and Dawe (1993) was published on a crossbedded configuration similar to the experiment described in this paper.

These different configurations show that the observed behaviour is a competition of non linear processes between capillary, gravity, and viscous forces. The relative importance of these effects depends on the rocks properties and the boundary conditions, and is dependent upon the geometrical properties of the system. This suggested that experiments should be performed with an average direction of the flow different from the orientation of the layers in a stratified system.

EXPERIMENTAL

Heterogeneous media

The heterogeneous media consisted of three blocks of porous material connected at a layer angle of 45 degrees inclination, see Fig 1. The capillary contact between the strata was ensured using a filter paper. Each block was 5 cm thick and the height was 5 cm. The medium was coated with epoxy resin reinforced with fiberglass to ensure a tight sealing and to maintain a pressure on the blocks to obtain capillary contact.

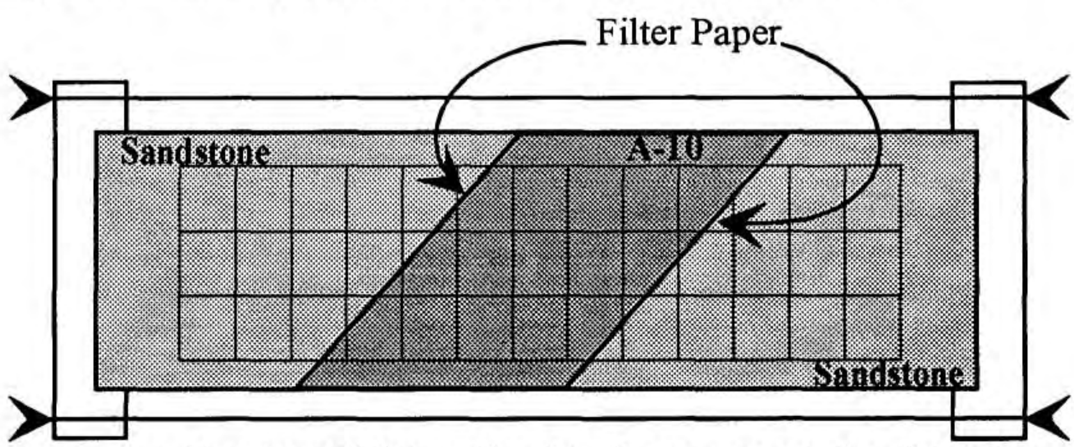

Figure 1 : Experimental Setup (the thin lines represent the distribution of measurement points)

Core material

The core material used for the first and the last block was consolidated sandstone. The Vosges sandstone from east France was selected because this material has successfully been used in previous experiments and experience has been obtained on the rock characteristics and the petrophysical properties are quite well known. This sandstone has typically a permeability of 500-700 mD and a porosity of 25%. Prior to the experiments on the heterogeneous media, core data on Block 1 and Block 3 was obtained, using adjacent pieces of core material. Porosity was determined by saturated weights and found to be 26%, and absolute permeability was measured to 550mD. Capillary pressure curves by the use of a centrifuge and mercury injection were obtained and pore size distributions were determined. Core data are found in Table 1.

The porous material used for the center block was Aerolith 10 (A-10), an artificial sintered porous media of high porosity and permeabilty, made by aluminum and silica. This material has also successfully been used before in similar experiments (Bertin et al., 1990), and characteristics are well known and can be found in Hamon and Vidal (1986). Further core data are listed in Table 1.

Experimental outline

The heterogeneous medium was evacuated and saturated with brine, 5% NaI in distilled water. Permeability and porosity of the composite medium was measured to 980 mD and 22%, respectively. Fluid properties are found in Table 2.

A sequence of immiscible floods were performed on the heterogeneous medium: primary drainage performed at high flow-rate, waterflood and finally a secondary drainage performed at a low flow rate. A gamma attenuation imaging technique successfully used in previous experiments, (Bertin et al., 1990), was used to image the development of the saturation fields. The sodium iodide salt in the brine is used to increase the absorption contrast between oil and water and improve the accuracy of the saturation measurement. The local fluid saturations were measured in-situ in a 2-dimensional grid pattern during the waterflood and secondary drainage. A 2D porosity map was also obtained using the gamma attenuation apparatus, see Fig. 2.

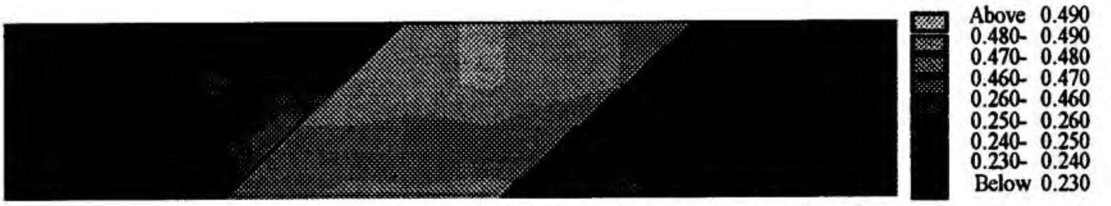

Figure 2 : Porosity field of the heterogeneous medium

RESULTS AND DISCUSSION

Primary Drainage.

The oil used in the primary drainage was a white mineral oil, Marcol 52, with a viscosity of 11.5 cp at room temperature. A high rate oilflood, 5 ml/min, was performed to obtain a low reduced water saturation. The saturation distribution at immobile water saturation was recorded, see Fig 3.

Figure 3 : Initial water saturation field after the first drainage.

After the oil flood, during a subsequent no flow period of 65 hours, the evolution of the saturation field is recorded. The results are presented in Figure 4 in terms of average saturation computed in the 3 blocks as a function of time. In this Figure, we observe a decrease of the average water saturation in block 2 (low capillary medium) while the water saturation increases slightly in the blocks 1 and 3. This behaviour has been observed in several other experiments (*e.g.* Alhanai et al.; 1992). It is characteristic of the capillary equilibrium process between two layers of different physical properties. During the drainage process, viscous effects are dominant and, immediatly after stopping the oilflow, there is no capillary equilibrium in the medium. Then imbibition and drainage processes occur betweeen the different media until a final saturation field is reached corresponding to static capillary equilibrium. The phenomenon we observe corresponds to the modification of saturation due to the capillary equilibrium, driving fluids across the boundaries.

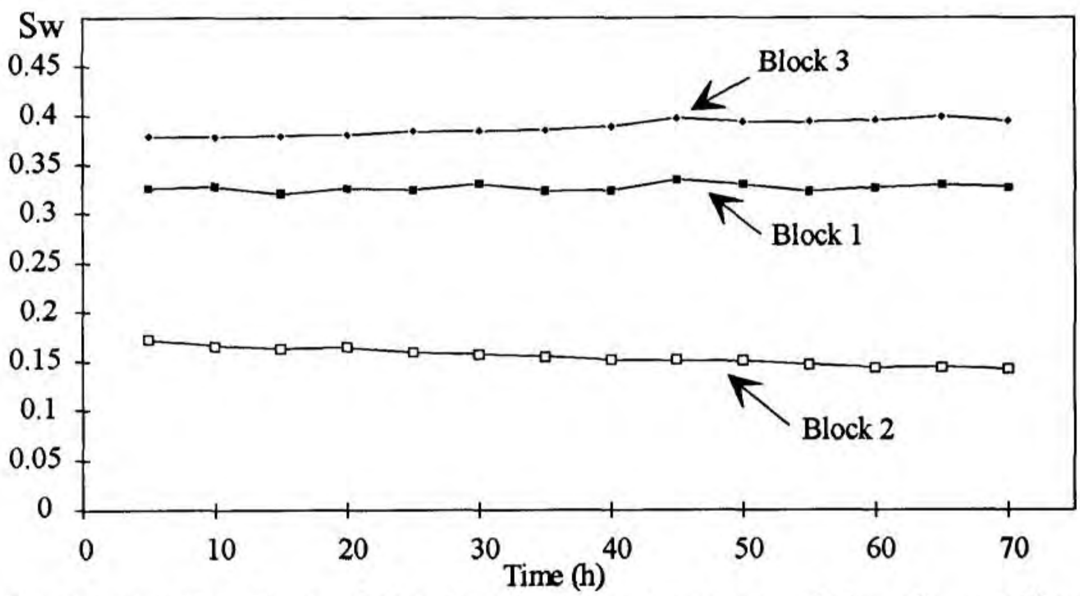

Figure 4 : Evolution of the Initial Water saturation during the capillary equilibrium process

The displacement of brine was more efficient in Block 1 compared to Block 3. This is believed to be an effect of the direction of flow and of the significant end-effect at the outlet of Block 3. The end-effect in Block 1 was not apparent under the applied capillary number in this displacement.

At the end of the drainage process, the relative permeability to oil was equal to 0.79.

Waterflood.

The waterflood was carried out with an injection rate of 6 ml/hour, corresponding almost to a frontal velocity of 30 cm/day. The 2D saturation field was measured with a 14 x 4 grid, once per hour. The counting time on each position was 25 sec. The recording time required to measure the entire field was 27 min., and hence small compared to the time for noticeable change in the saturation field to take place. Thus no correction of saturation distributions was necessary. Water breakthrough occurred when .38PV of brine had been injected. Time development of the water bank is shown in Fig. 5.

After injection of almost 3 PV of brine, there is a significant difference of oil recovery in the different layers. A higher recovery is observed in the low capillary block than in the higher capillary medium. This is in agreement with the behaviour of the isolated samples. However, the time evolution of water saturation field (Figure 5) shows a significant different recovery in the upper and lower part of the central block, while the saturation field in the sandstones layers are regular as expected. This particular behaviour is discussed in the following :

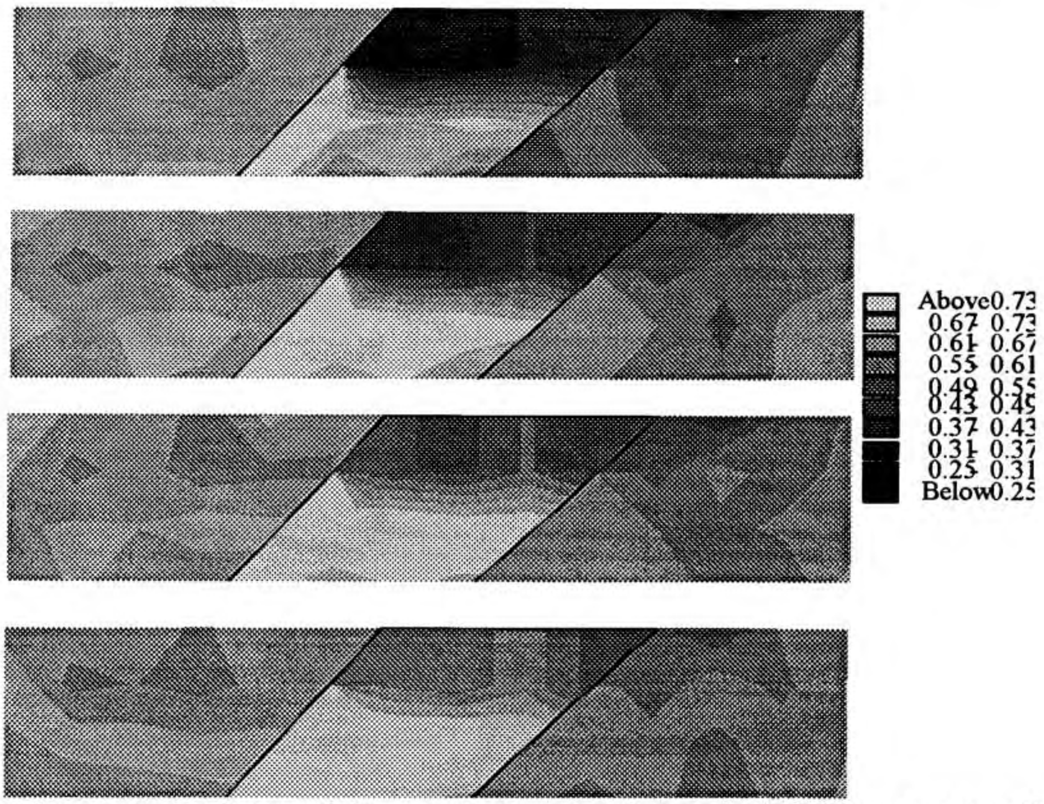

Figure 5 : Evolution of the water saturation during the imbibition process (the saturation fields are represented from top to bottom every 3 hours).

* In the low capillary medium, A-10, there is a competition between the gravity and capillary forces. For this particular geometry, water enters first the bottom of the central block and, due to viscous forces, flows through it towards the third block. Thus, in the A-10 block, water imbibes the medium upwards in competition with gravity. This gravity effect is of the same order of magnitude as the capillary pressure when Sw is between 0.3 and 0.7. This is due to the characteristic of the capillary pressure curves. The flow behaviour is different in the sandstone because the slope of the curve is much steeper and a slight modification of capillary pressure induces less difference in terms of saturation.
* The poor sweep efficiency in the upper part of Block 2 might be an artefact of loss of communication between the blocks when constructing the composite medium (*e.g.* local imperviousness due to epoxy penetration or change of wettability of the filter paper) prohibiting the flow of water to enter the top Block 2.

* The waterflood experiment was performed during the time required to inject 3 PV. This time period may be too small to obtain a complete recovery of all the mobile oil contained in the A-10 by imbibition, considering that the imbibition normal to the main flow is a slow process.

Second Drainage.

The flow rate during the second oilflood was set to 2 ml/hour, corresponding to a frontal velocity of almost 10 cm/day. This was to be able to detect capillary effects when the viscous force was reduced; the same oil was still in use. Due to this slow injection rate the saturation field could be measured in a finer grid. The detector positions were selected according to a grid of 20 x 6 points. The time for acquiring data for one grid was one hour. The development of the saturation fields during the second oilflood is shown in Fig. 6.

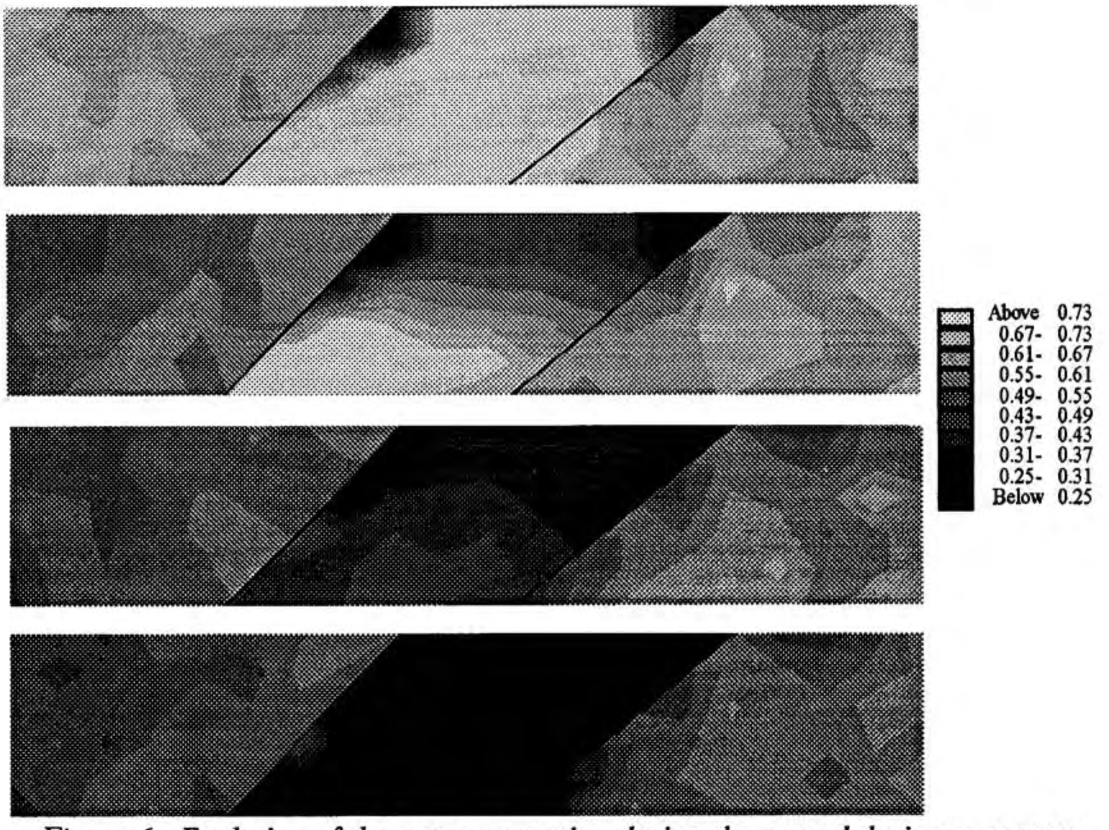

Figure 6 : Evolution of the water saturation during the second drainage process (the saturation fields are represented from top to bottom every 5 hours).

During the oilflood of the central block, we observed an oil displacement through the upper part of the block. This may be attributed to gravity and relative permeability effects, the relative permeability to oil was initially high due to the poor recovery of oil in this region during the previous waterflood, however, at the end of the drainage process we obtain a saturation field (Figure 7) corresponding to the capillary equilibrium as described before. In this experiment, due to the low value of the oil flow-rate, we observe a significant end effect in Block 3.

Figure 7 : Initial water saturation field at the end of the second drainage.

The recovery of the wetting phase was higher in the low capillary zone compared to the high capillary zone. The sweep was better at the inlet end of the core than at the oulet end, due to end effects.

CONCLUSIONS

- The impacts from capillary heterogeneities on cross flow in a dipping reservoir have been experimentally visualized.
- Combining effluent analysis to in-situ 2D fluid saturation information improved the description of the oil recovery.
- Obtaining two-dimensional local saturation information in larger slabs of porous rocks improves the interpretation of the recovery mechanisms in heterogeneous media.
- Capillary end effects and dip angle are shown to strongly influence on oil recovery by waterflooding.

MEDIUM	Porosity	Kw	Swi	Sor
Sandstone	25 %	554 $10^{-15}m^2$	31 %	38.5 %
Aerolith-10	44.7 %	5.1 $10^{-12}m^2$	15.4%	17.4 %

Table 1 : Physical properties of the porous media

FLUID	Oil	Brine
ρ (Kg/m^3)	835	1045
μ (mPa.s)	11.5	1.

Table 2 : Physical properties of the fluids.

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