TWO-PHASE FLOW IN HETEROGENEOUS NODULAR POROUS MEDIA.

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Abstract In this paper we present experimental results dealing with the flow of two immiscible fluids (drainage and imbibition) in nodular media with three different configurations.

1. Type I medium consists of three plugs of sandstone embedded in sand (both media being water-wet)
2. Type II medium consists in sand packed down in three holes drilled in sandstone (both media being water-wet).
3. Type III medium consists in an oil-wet sand (treated by silanization) packed down in three holes drilled in a water-wet sandstone.

The physical properties (porosity, permeabilities, capillary pressure, end-point saturations) of the regions composing the media were measured independently on isolated samples. During the drainage and imbibition experiments, the saturation was measured using a γ-ray attenuation apparatus.

After the drainage process, the initial water saturations are found different depending on wether the nodules are more permeable (sand) or less permeable (sandstone) than the continuous region. The values of saturation in the nodules and the continuous region are lower in the Type II medium than in Type I. In the case of oil-wet nodules, the initial water saturation in the nodules is found lower than in the other configurations.

The waterflooding of Type I medium presents a classical behaviour (breakthrough after 0.3 PV of water injected and low recovery). The behaviour of Type II experiment is different and shows a non-classical recovery curve. Oil recovery from the sandstone ciesed after injecting about 0.3 PV of water, whereas the recovery from the sand continued even after injecting more than 30 PV. In Type III medium (nodules made of oil-wet sand), oil recovery from the sandstone has the same behaviour as in Type II experiment but we could not displace the oil trapped in the nodules.

INTRODUCTION

Two-phase flow in heterogeneous porous media is a problem of central importance in oil recovery because most of the reservoirs are heterogeneous and fluid flow is the most significant transport phenomenon.

In order to predict the behaviour of a given reservoir, numerical methods are developed to determine the areal distribution of saturations. To provide such results, a correct multiphase simulation model requires not only a precise description of the reservoir's heterogeneity but also a detailed formulation of the physics involved, therefore a precise description of the flow of immiscible fluids in heterogeneous systems is needed.

Different experimental studies have been reported in the literature dealing with two-phase flow in stratified media with flow parallel to the strata (Ogandjanzanc, 1960; Dasse, 1965; Novosad et al., 1984; Sorbie et al., 1984, Ahmed et al., 1988, Quintard et al., 1989, Bertin et al., 1990a and b). There are also studies dealing with stratified systems with the flow being normal to the strata (Hinkley and Davis, 1986, Laribi et al., 1990) and only a few studies dealing with the flow of immiscible fluids in nodular systems (Alhanai, 1991; Alhanai et al., 1992; Bertin et al., 1992; Dawe et al., 1992).

In this paper we will present experimental results dealing with the drainage and imbibition of different nodular media. The theoretical interpretation of these experiments, using the large-scale averaging concept, have be done elsewhere (Quintard and Whitaker, 1988; Alhanai et al., 1992) and will not be developed here.

EXPERIMENTAL SET-UP

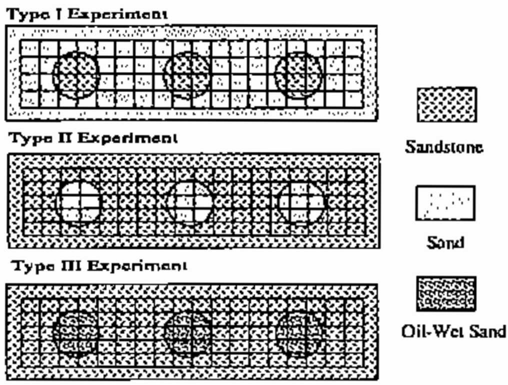


FIGURE 1 Experimental configurations

Three heterogeneous nodular models (Type I to III represented in Figure 1) were designed and prepared in the laboratory, such that their 3D geometry allowed the reduction of the flow problem to 2D for laboratory simulation (Figure 2).

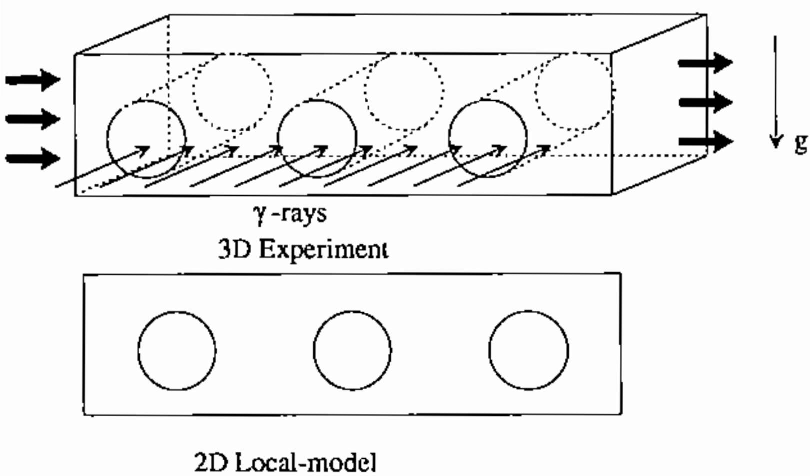


FIGURE 2 3D and 2 D models of the nodular systems

The porous materials chosen to construct the two regions are described below

(i) The η-region is a sandstone of low permeability (15 mDarcy) coming from the Vosgian quarry of Adamswiller (France)

(ii) The ω-region is fine, pure silica sand of controlled granulometry (permeability is equal to 7.4 Darcy)

(iii) The ω-region in Type III Experiment is the same sand but treated by a silanization process to provide an oil-wet medium.

Each material by itself is assumed to be homogeneous, isotropic and water-wet (except for the sand in Type III Experiment). For each porous medium used in these experiments we carried out two-phase flow experiments to provide local-scale properties (porosity, permeabilities, and capillary pressure). The reference properties for the two regions are listed below.

Table 1 Physical properties of the media

	ε(%)	K ($10^{-12}m^2$)	S_{wi}	$K_O(S_{wi})$ ($10^{-12}m^2$)	S_{or}
Sandstone	18.5	0.015	32.2	0.018	38.
Sand	43.7	7.4	14.1	5.25	30.

EXPERIMENTS

Type I experiment: The nodules are made of sandstone plugs coming from Type II experiment, embedded in the sand. The two media are water-wet.

Type II experiment: The nodules are made of sand packed down in holes drilled in the continuous region made of sandstone. The two media are water-wet.

Type III experiment: This experiment is similar to Type II experiment, the sand used to build the nodules is made oil-wet by a silanization process to obtain a wettability contrast in addition to the permeability heterogeneity.

Corresponding to the three nodular systems, three experiments were conducted; each comprising a drainage displacement followed by waterflood. They are carried out in a way similar to the tests on isolated samples:

1. Each model was evacuated and then filled with metered volume of the brine to determine its pore volume and average porosity. This was followed by *in-situ* measurement of the porosity field by γ-ray attenuation (Nicholls and Heaviside, 1985). The absolute permeability, K, was measured classically at this stage.

2. The second step was an oil-flood to drive the systems to their initial water saturations, S_{wi}. Oil was injected at a constant flow-rate of 180 cc/h until water production ceased at the outlet of the system and the pressure drop became constant. The initial water saturation fields were measured after few days necessary to achieve the capillary equilibrium between the two regions.

3. The last step was a water flood to drive the models to their residual oil saturations. The water was flood for several hours at a constant flow-rate (4.8 cc/h for Type I Experiment and 3 cc/h for Types II and III Experiments, corresponding to filtration velocities of $6.6\ 10^{-7}$ m/s), while constantly recording the oil recovery and pressure drop. Moreover, the evolution with time of the 2D water saturation fields were recorded regularly by γ-ray attenuation over 2D regular grids represented in Figures 1. A photon counting time of 20 seconds per point allowed the whole saturation field to be recorded once every about half-hour. This monitoring was frequent enough to permit the capturing of rapid saturation changes during the early injection phase, since the waterflood all-together lasted over 20 hours. For Type II experiment, however, the saturation measurement network was switched to a finer 38 x 10 grid after about 1 pore volume of brine had been injected, to enhance the detection of the spatial distribution of local porosity and the initial water saturation in the two regions and, in particular, across the interfaces.

The experimental results for each model are reported and analysed below as per displacement type.

DRAINAGE EXPERIMENTS

The drainage experiments were used to settle an initial oil-water saturation in the porous system before the waterflooding experiments. Since these displacements were performed at a relatively high oil flow-rate, the data essentially available are saturations at steady state. In the following discussion we will denote by $S^*_{w\omega}$ and $S^*_{w\eta}$ the averaged saturations associated with the ω (sand) and the η (sandstone) regions respectively (averaging volumes correspond to zones defined in Figure 5), while the irreducible saturations measured on isolated samples are denoted $S_{w\omega i}$ and $S_{w\eta l}$ (local values).

Assuming that a good capillary pressure junction had been provided across the interface between the two regions during the construction of the nodular systems, the oil and water pressures, and hence the phase pressure difference, are continuous across the nodular systems. However, the saturation distribution is discontinuous across the interfaces, since the local saturation values on each side of the interfaces are determined by the individual (local) capillary pressure curves shown in Figure 3. The water saturations measured at the end of the drainage process are reported in the same figure for Type I and II experiments. The results are discussed here below.

Type I Experiment

According to the capillary-equilibrium condition, the continuous region should drain its water until it attains its irreducible value $S_{w\omega i}$. On the other hand, and because of the capillary pressure continuity between the regions, the desaturation of the nodular region is governed by the relation

$$S_{w\eta} = p_c^{-1}\left[p_{c\omega}(S_{w\omega i})\right] \tag{1}$$

These two values are reported in Figure 3 represented by arrows. When $S_{w\omega} = S_{w\omega i}$, the water relative permeability in the continuous region becomes zero and the water is trapped in the nodule at a saturation given by Equation (1). The experimental points corresponding to the measured values of the saturation averaged over each region, are reported in Figure 2 by triangles. We have a good agreement between the quasi-static prediction and the experimental results.

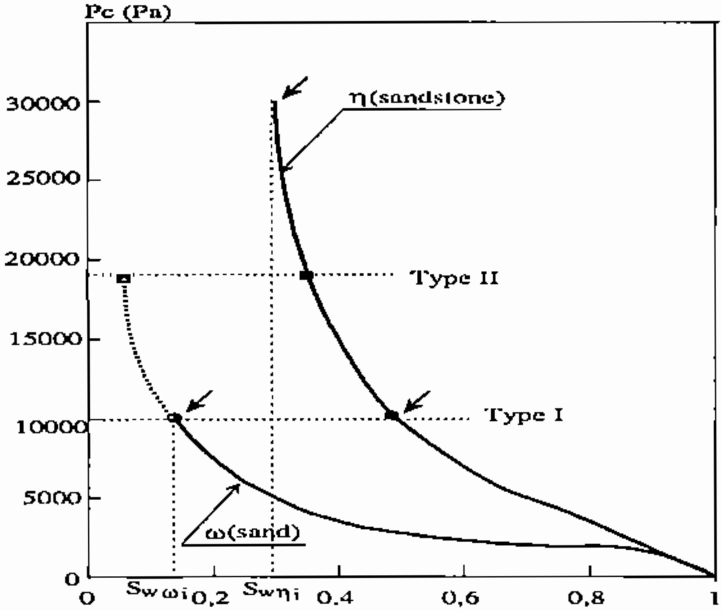


FIGURE 3 Type I and II Experiments: local capilllary pressure curves and water saturations at the end of the drainage process.

Type II Experiment

According to the capillary equilibrium condition, the two regions should desaturate according to Equation (1) until $S_{w\omega} = S_{w\omega i}$, then the nodules become inactive zones while the continuous region can desaturate until $S_{w\eta} = S_{w\eta i}$, these theoretical quasi-static values are reported in Figure 3 by arrows. The experimental points reported in Figure 3 by squares, show that $S_{w\omega}$ is significantly smaller than the value measured on isolated samples, while $S_{w\eta}$ is lower than $S_{w\eta i}$. This latter value can be explained by an incomplete drainage process, but the measured water saturation in the nodules requires another explanation.

"Irreducible" saturation is not an intrinsic property of a porous medium. Rather, it is a process-dependent property that is determined by the interactions of several flow conditions and of the rock/fluid system properties (e.g. porosity, flow velocities, fluid viscosities, wettability, capillary and film flow effects, lubrication effect, presence of local heterogeneities, etc.). This dependence of the "irreducible" saturation on the particular process and system being investigated suggests that both capillary pressure and relative permeability curves are likewise process-dependent, particularly near the end-point saturations, and that neither one of these curves could be viewed as an intrinsic property of the porous medium alone. This means that some adjustment to the saturation functions should perhaps be applied if they are to successfully describe a particular process in a particular rock/fluid system. In our case, the adjustment is to simply extrapolate the regional drainage saturation functions of the nodules to the observed irreducible water saturation. The question whether these extensions can be defined in an intrinsic manner independent of the heterogeneous system we are studying is very important from the point of view of scaling-up methods.

Type III Experiment

This experiment is similar to the Type II Experiment except that the sand used to make the nodules has been treated by a silanization process to make it oil-wet. In Figure 4 we have plotted the local water saturation measured in a section of the porous medium including a nodule.

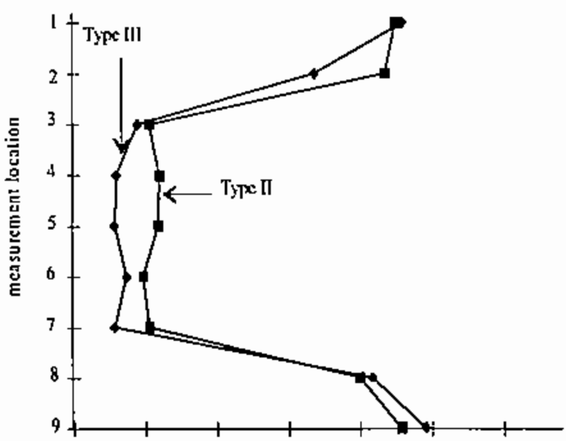


FIGURE 4 Type III Experiment: local saturation profile measured along a cross section

These results show a saturation jump between the nodule and the continuous region. If we compare these results with the ones obtained with Type II Experiment (Figure 4) we notice that the saturation in the sandstone is quite similar but that a slight difference exists in the nodule.

WATERFLOODING EXPERIMENTS

The saturation fields obtained after the drainage experiments reported above are used as initial conditions for the waterflooding experiments described here below.

During the experiments, performed at a constant water flow-rate corresponding to aproximatively a front velocity of 30 cm/day, we record the oil recovery, the pressure drop along the core and the *in-situ* water saturation fields using the two-dimensional γ-ray attenuation apparatus.

Type I Experiment

Figure 5 shows the time evolution of the water volume fraction averaged over a zone (a zone is defined as a nodule and the continuous region surrounding it).

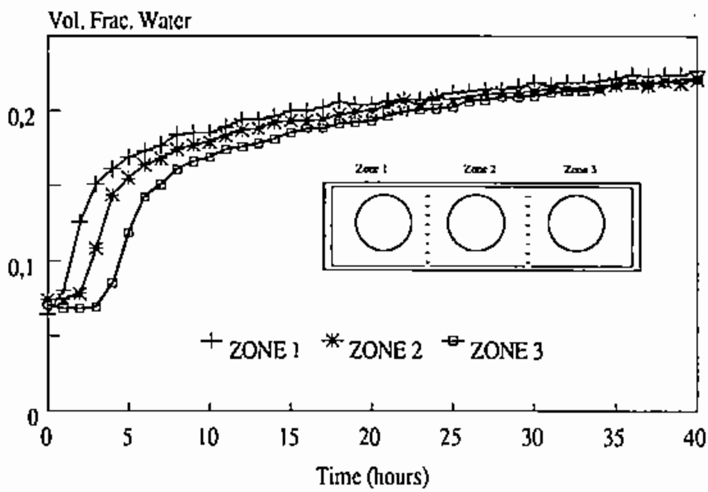
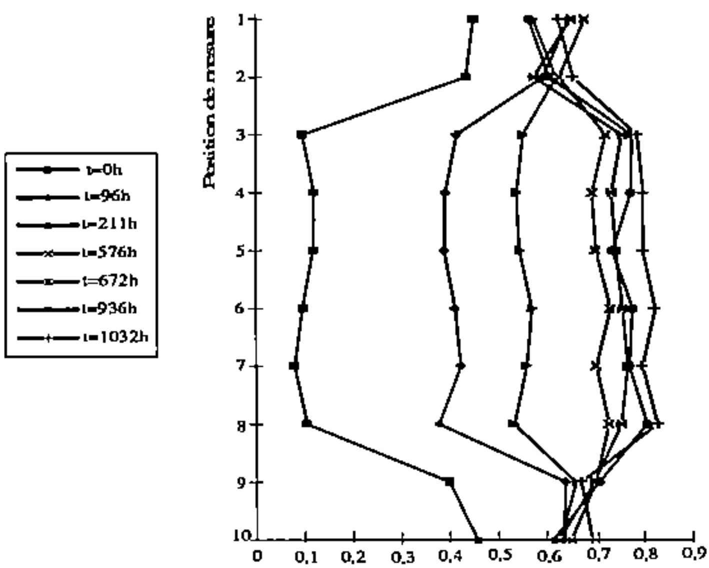


FIGURE 5 Type I Experiment: averaged volume fraction versus time

The nodules reach their residual-oil saturation and become inactives zones (the relative permeability to oil is equal to zero), while the oil flow can continue in the continuous region until it reaches the saturation limit. At the end of the waterflooding the obtained values of the final saturations are close to the ones measured on isolated samples (local values). This experiment has been interpreted satisfactorily by Alhanai (1991) and Alhanai et al. (1992) in the framework of the quasi-static large-scale averaging method. In the quasi-static model, saturation fields are locally at a quasi-steady capillary equilibrium. This requires that capillary forces are sufficiently large to ensure a locally quasi-uniform capillary pressure field, which is the case in Type I experiment.

Type II Experiment

The behaviour of this experiment is much more complex than that of the previous one. To present more precisely the evolution of the *in-situ* evolution of the water saturation we used a finer grid of measurement points (38 x 10) and plotted the evolution of the water saturation measured in a section of the porous medium including a nodule (Figure 6).



At the earliest times of the waterflooding experiment, we observe an increase of the water saturation in the continuous region (sandstone) until it reaches its residual-oil saturation (this value is the same as that measured on isolated sample), while the saturation in the nodules (sand) is lower than its final value. After this stage, we observe a very low increase of the water saturation in the sand until it reaches a maximum value, while the water saturation in the continuous region does not vary significantly. This behaviour is clearly showed in Figure 7 where we plotted the evolution with time of the volume fraction averaged over the three zones constituing the heterogeneous porous medium.

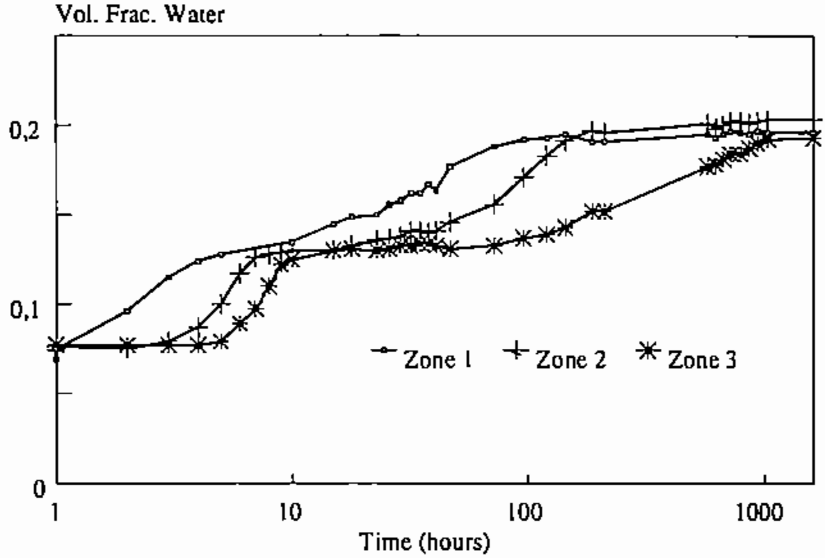


FIGURE 7 Type II Experiment : averaged volume fraction versus time

We observe two stages of the recovery process. The first stage corresponds to a complete recovery in the sandstone and a low increase of water saturation in the nodule (sand). The second stage corresponds to a slow recovery in the nodules until reaching its saturation limit. This behaviour is obviously non quasi-static, it can be explained by the existence of capillary pressure gradients at the interface between the two regions.

The difference between a quasi-static (type I) and a non quasi-static (Type II) experiment is illustrated in Figure 8 where we plotted the evolution of the capillary pressure difference δP_C as a function of time

$$\delta P_C = P_C(\text{continuous region}) - P_C(\text{nodule}) \qquad (2)$$

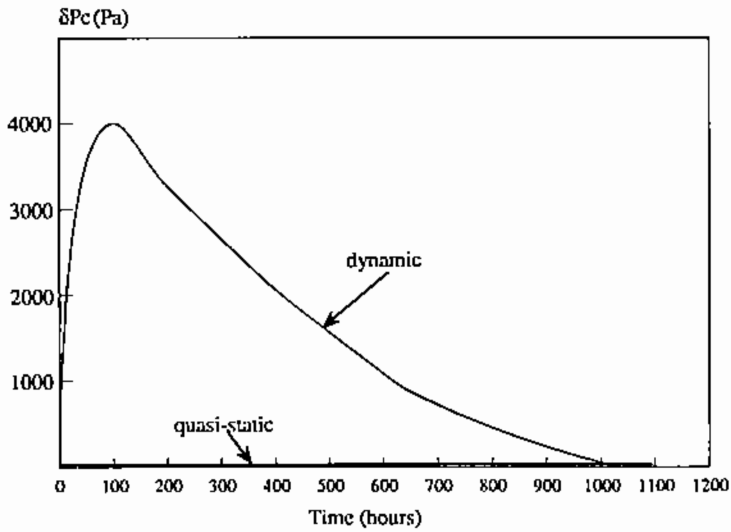


FIGURE 8 Capillary pressure difference

The quasi-static behaviour corresponds to saturation values corresponding to δP_C always equal to zero while the non quasi-static behaviour shows a fast increase of δP_C followed by a slow relaxation of the capillary pressure gradients.

This non quasi-static behaviour have been confirmed by a numerical simulation of the waterflooding of Type I Experiment (sand embedded in sandstone) performed using the SCORE model. In Figure 9 we plotted the evolution of the fractional flow of water as a function of time. We observe two stages in the evolution of the recovery, this is qualitatively in good agreement with the experimental observations described before.

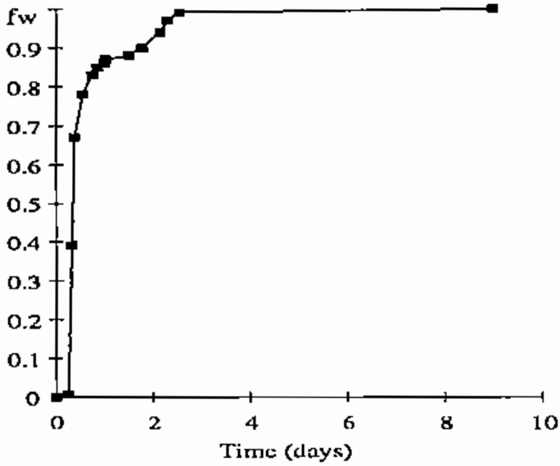


FIGURE 9 Type II Experiment: numerical evolution of the fractional flow of water versus time

Type III Experiment:

In Figure 10 we have plotted the evolution of the water saturation in a section of the porous medium including a nodule.

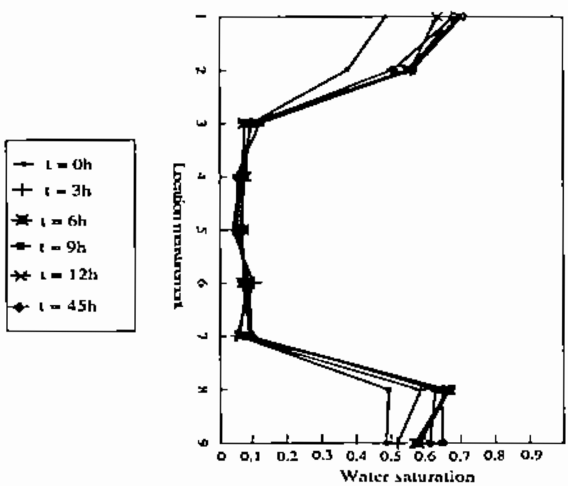


FIGURE 10 Type III Experiment: local water saturation measured at a cross section

The waterflooding behaviour can be described as follows: (i) The water saturation increases rapidly in the sandstone until reaching its limit value (corresponding to the residual-oil saturation measured on isolated sample), (ii) the water do not enter in the oil-wet nodule, there is no oil displacement and the water saturation stays at its initial value. During the waterflooding, we increase the pressure in the water phase until reaching a zero capillary pressure in the continuous region (water-wet sandstone). The water being in residual form (for example as discontinuous globules), the increase of the non-wetting phase pressure does not allow the flow of oil out of the nodules.

CONCLUSION

Experimental results presented in this paper show that nodular heterogeneous systems feature a non trivial behaviour. Our results show essentially that there is a dramatic change in the behaviour of a nodular system if properties of the nodules and the continuous regions are interchanged.

The saturations at the end of the drainage process are well predicted by the quasi-static approach for Type I Experiment but, on the contrary, corrections of the local capillary pressure curves are required to interpret Type II Experiment.

The waterflooding behaviour of the three experiments carried out is schematically illustrated in Figure 11.

Type I Experiment (sandstone in sand) shows a quasi-static behaviour, the increase of water saturation is constant in both regions. The behaviour of Type II Experiment is different; the water saturation reaches its maximum value in the sandstone while the nodule remains largely oil-saturated. The oil contained in the nodule flows slowly and the final configuration corresponds to residual oil saturations in the two regions. During the waterflooding of Type III Experiment, the oil contained in the oil-wet nodule does not change significantly.

These results are of great interest for the petrophysics engineer who had to determine experimentally the physical properties of cores coming for the reservoir because they are always heterogeneous. Our study shows the necessity of local measurement of the saturation during drainage and imbibition experiments to determine the topology of the heterogeneities.

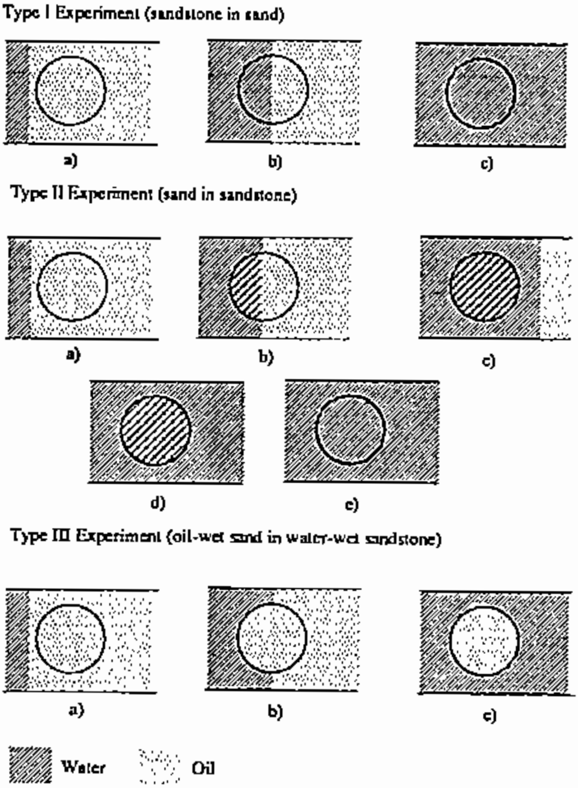


FIGURE 11 Schematic waterfloofing behaviour of the nodular systems

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REFERENCES

AHMED, G., CASTANIER, L. and BRIGHAM, W.E., 1988, An experimental study of water-flooding from a two-dimensional layered sand model, *SPE Reservoir Engineering* 3 (1): 45-54.

ALHANAI, W., 1991, Multi-phase flow in heterogeneous porous media: theoretical and experimental results for nodular systems, *Thèse Université de Bordeaux I.*

ALHANAI, W., BERTIN, H. and QUINTARD, M., 1992, Two-phase flow in nodular systems: laboratory experiments. *Rev. Inst. Franç. du Pétrole,* 47, 1, 29-44.

BERTIN, H., QUINTARD, M., CORPEL, Ph. V. and WHITAKER, S., 1990a, Ecoulement polyphasique dans un milieu poreux stratifié: résultats expérimentaux et interprétation par la méthode de prise de moyenne à grande échelle. *Rev. Inst. Franç. du Pétrole,* Vol. 45, N° 2, 205-230.

BERTIN, H., QUINTARD, M., CORPEL, PH. V. and WHITAKER S., 1990b, Two-phase flow in heterogeneous porous media III: laboratory experiments for flow parallel to a stratified system. *Tansport in Porous Media,* 5, 543-590.

BERTIN, H., ALHANAI, W. and QUINTARD, M., 1992, Ecoulements polyphasiques dans un milieu poreux hétérogène de type nodulaire: drainage initial. *C.R. Acad. Sc. Paris,* t. 314, *Série II,* 431-437.

DASSE, H., 1965, Déplacement d'un fluide par un autre non miscible dans un milieu poreux constitué par deux strates de perméabilités différentes. *Rev. Inst. Franç. du Pétrole,* 20, 10, 1462-1474.

DAWE, R.A., WHEAT, M.R. and BIDNER, S., 1992, Experimental investigation of capillary pressure effects on immiscible displacement in lensed and layered porous media. *Transport in Porous Media,* 7, 83-101.

HINKLEY, R.E. and DAVIS, L.A., 1986, Capillary pressure discontinuities and end effects in homogeneous composite cores: effect of flow-rate and wettability. SPE 15596.

LARIBI, S., BERTIN, H. and QUINTARD, M., 1990, Ecoulements polyphasiques quasi-statiques en milieu poreux stratifiés: résultats expérimentaux et interprétation, *C.R. Acad. Sc. Paris,* t. 311, *Série II,* 271-276.

NICHOLLS, C.I.,and HEAVISIDE, J., 1985, Gamma-ray absorption techniques improve analysis of core displacement test. SPE 14421.

NOVOSAD, J., IONESCU-FORNICIOV, E. and MANNHARDT, K., 1984, Polymer flooding in stratified cores, *35th Annual Technical Meeting of the Petroleum Society of CIM,* 909-921.

OGANDJANZANC, V.G., 1960, Recherches expérimentales sur le déplacement du pétrole dans les roches magasins hétérogènes, *Izv., Akad., Nauk. SSSR*, 129-137.

QUINTARD, M. and WHITAKER, S., 1988, Two-phase flow in heterogeneous porous media: the method of large-scale averaging. *Transport in Porous Media,* 3, 357-413.

SORBIE, K.S., SWAT, R.M. and ROWE, T.C., 1987, Oil displacement experiments in heterogeneous cores. Analysis of recovery mechanisms. Trans. AIME SPE, SPE 16706.