EFFECTS OF CORE SAMPLE DIMENSIONS AND ORIENTATION ON TWO-PHASE FLOW PROPERTIES DETERMINATION.

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Abstract.

Two-phase flow properties determination for water/oil systems is one of the most important tasks of Core Analysts. This work is based firstly on an experimental approach (corefloods) and secondly on an appropriate numerical interpretation (history matching using a one-dimensional model based on generalized Darcy's law). Consequently, the quality of the relative permeability and capillary pressure curves depends strongly on the quality of the core sample selection as well as on its representativity. This is particularly true in the case of heterogeneous reservoirs for which the selected core sample should be free of important heterogeneities at its scale in order to obtain appropriate results.

The aim of this study was to investigate as completely as possible the influence of core sample dimensions (full size or whole rock versus plugs) and orientations (vertical versus horizontal) on the two-phase flow properties and deduce some recommendations for laboratory experiments. In this study, a "vertical" sample is a core sample drilled perpendicular to the reservoir laminations, and an "horizontal" sample is a core sample drilled parallel to the reservoir laminations. Of course, many other parameters such as core sample preparation, wettability restoration, experimental conditions, type of experiments (steady state or unsteady state), etc ... may influence the final results. They were not the purpose of this study, and therefore have been kept constant during this work.

Introduction.

The question of using "full size" (diameter between 7.6 and 10 cm , and length between 20 and 25 cm) or "big plug" (diameter between 3 and 5 cm, and length between 5 and 7 cm) core samples for two-phase flow displacements is generally raised for laboratory reasons (size of the apparatus, possibility to carry out several corefloods at the same time, time needed for the preparation of the samples and the experiments, etc ...). However, some other considerations on the reservoir may lead to a more serious reflexion on the core dimension and/or orientation in order to obtain the most appropriate results. This is particularly true in the case of a laminated reservoir where the flow is "almost" parallel to the laminations, whereas it will be perpendicular to the laminations during coreflood on a full size. The idea of taking horizontal plugs in order to respect at the laboratory scale the phenomena involved in the reservoir is worth being studied precisely. Unfortunately, things are not that simple, and this study will try to clarify and identify the advantages and disadantages of each solution.

The experiments were carried out on core samples coming from a North Sea oil reservoir where thin horizontal laminations have been previously identified.

Experimental program.

A "full size" core sample (10 cm in diameter and 20.4 cm in length) coming from this North Sea oil reservoir was selected based on classical CT Scan, Gamma density, minipermeameter and acoustic measurements. This reservoir was known for having slight horizontal laminations at the core sample scale, and Reservoir Engineers were concerned by the representativity of experiments carried out on vertical samples.

First, a waterflood experiment was carried out on this full size sample using the classical Elf procedure (described in Labastie *et al.*, 1980; Gauchet, 1992). Then, two "big plugs" (5 cm in diameter and 8.5 cm in length) were drilled from the previous core sample, one horizontally and the second vertically. Waterfloods were also carried out on these plugs with, in addition, gammaray saturation monitoring. Bumps were performed at the end of each coreflood. Exactly the same experimental conditions (frontal velocity) have been respected in each of these experiments, including the injection rate increases.

Numerical interpretations (history matching) of these three unsteady state experiments were performed independantly using a specialized one-dimensional simulator based on generalized Darcy's law. Comparisons between the various relative permeability curves obtained were performed and effects on recovery evaluation of using inappropriate curves were investigated.

Results and discussions.

The main experimental data are summarized in table 1. The relative permeability curves obtained in these three cases are shown on fig. 1 to 3 and they are compared on fig. 4. The water saturation profiles during these experiments (gammaray monitoring) are illustrated in fig. 9 and 10. The results of each numerical interpretation are shown on fig. 5 to 7. Finally, the possibility to reproduce numerically the saturation profiles with this simulator is illustrated in fig. 8.

Comparison between vertical full size and vertical plug (size effects)

A quick observation leads to the conclusion that the general trends of these two sets of curves are rather similar. However, a more careful analysis allows identification of some differences which can be described as follows.

First of all, the remaining oil saturations (ROS) at the end of each injection rate step are not similar. In the full size case, ROS varies from 36.6 % (at the end of the first injection rate) down to 20.8 % (after injection rate increases), while this variation is from 23.3 % down to 21.4 % in the vertical plug case (see table 1). This may be explained by a core sample dimension effect. The gammaray saturation monitoring (fig. 9) showed that end effects are present even at high injection rates on plugs. They can influence as much as the last 2.5 cm of the core, which represents 30 % of the total plug length. Consequently, the ROS variation, which depends mainly on the increases along the asymptotic part of the saturation profile due to the step rate increments (Gauchet, 1992), can not be as large in the case of a plug sample. Secondly, the percentage of the total length affected by end effects (region where the residual oil saturation is not reached) is much higher in the case of the plug sample. Thus, the residual oil saturation (SOR) measured on plug samples can be over estimated. Finally, the final capillary pressure reachable is higher in the case of the full size than in case of plugs. As it has been already discussed in some previous paper (Wood *et al.*, 1991; Gauchet, 1992), the residual oil saturation in non water wet case is dependent of the final capillary pressure.

Also, the use of plug samples for corefloods is disadvantaged by an other point : a loss in experimental data acquisition accuracy. The measurement accuracy depends directly on the kind of apparatus used, which is almost a constant for each coreflood experiment. Hence, the same reading precision is obtained in every case. As the use of a plug sample can be characterized by a small pore volume, which induces a small amount of production and a small pressure drop between the inlet and outlet faces, the quality of the results obtained can not be as good as that obtained on full size.

Comparison between vertical plug and horizontal plug (orientation effects)

This time, the general trends and the end points are clearly not similar. Even the experimental behaviors are different (early breakthrough in the case of horizontal plug, lower pressure drop curve, etc ...).

When we look at the water saturation profiles, two different regions (layered system) can be identified on the horizontal plug by analysis of their different phase flow behavior (see experimental saturation profiles fig. 10). Then, in order to better identify and understand this behavior, the horizontal core sample was carefully examined at the end of the coreflood experiment with the help of a geologist. Two layers with an angle of about 30° with the core axis were pointed out. However, this difference was not big enough to be illustrated by a picture. Also, this heterogeneity was not detected by the CT Scan or gamma density measurements.

This layered system on the horizontal plug induces a premature breakthrough (after 0.02 pore volume injected) and an extended oil production. Classical history matching is then not accurate, as the numerical model is a one dimensional model. The relative permeability curves are not representative of a facies anymore and an incorrect pseudoization (homogeneization) process is included in the calculation. This experiment should be interpreted with a three dimensional (3 D) simulator knowing the 3 D microscale heterogeneities along the core sample in order to obtain correct relative permeability curves. This is not realistic in the case of core measurements and never performed. However, these heterogeneity problems have been extensively studied in the case of laminations parallel to the flow (Quintard *et al.*, 1988; Bertin *et al.*, 1990; Ingsoy *et al.*, 1994) or nodular heterogeneous media (Bertin *et al.*, 1992) at the large core scale and field scale.

Also, to perform coreflood on composite horizontal cores if the reservoir is laminated is something which may increase laboratory artefacts. In such case, in addition to heterogeneity problems due to laminations, continuity problems may occur due to the probable non or bad connection of the laminations (core sample are then coming from different depth and laminations can be slightly different).

If the reservoir is not layered at the core scale level, the use of horizontal plugs or vertical plugs for corefloods is equivalent. In this case, homogeneity problems disappear and, as the relative permeabilities are normalized by the oil permeability at initial water saturation, no difference will occur even if the horizontal absolute permeability is not equal to the vertical one.

Comparison between vertical full size and horizontal plug (size and orientation effects)

All the previous comments made on size and orientation effects are combined in this part.

However, a simple comparison at the relative permeabilities level is not enough to fully identify the effect on the recovery of using incorrect curves. For this purpose, we simulated the full size experiment using the relative permeabilities determined on the horizontal plug (fig. 11). As illustrated on fig. 11, the experimental data (oil production and pressure drop) are not reproduced at all and the final oil recovery varies from 51.9 % of oil in place using the correct curves to 46.5 % using the curves determined on the horizontal plug. As shown, the influence of using unadapted realtive permeability curves on the global recovery can be more important than previously thought.

The same kind of comparison was performed with the experimental data obtained on the vertical plug using the relative permeability curves determined on the horizontal plug (fig.12).

In the case of a laminated reservoir at the core scale (including the plug scale), heterogeneities can not be avoided during the core sample selection. In order to obtain representative results, the core sample size should allow a correct description of the reservoir laminations, and its orientation should be consistent with the numerical model used for pseudoization. The use of a full size sample will satisfy the first point as the risk of choosing a sample in a non representative zone is lower than for a plug. Concerning the orientation, the numerical interpretation will be performed with a 1 D model which allows simulation only of the heterogeneities perpendicular to the flow. In addition, these kind of heterogeneities are the easiest to identify and quantify (minipermeameter measurements on the surface for the permeability, and acoustic measurements perpendicular to the axis for porosity, which are non destructive). Hence, in a such case, a full size core sample with the heterogeneities perpendicular to the flow direction will be the best candidate. Of course, this solution should be avoided when other possibilities are available.

Conclusions.

The results of this study shows that, for a specific case of a North Sea oil reservoir, the following conclusions can be made :

- the use of plug size samples, instead of full size samples, to determine two-phase flow properties is detrimental to the quality of results (experimental accuracy, saturation profile heterogeneities due to end effects, early breakthrough, ...). Full size core samples should always be preferred.
- if, for some reasons, a coreflood is performed on a plug, a homogeneous plug should always be preferred, and saturation monitoring is essential.
- corefloods on laminated core samples are generally not appropriate as they induce incorrect pseudoization processes in the relative permeability determination. Hence, in the case of laminated reservoirs at core scale, the use of horizontal plugs should be avoided as heterogeneities parallel to the flow are not taken into account in the numerical analysis.
- CT Scanning is not always precise enough to identify fine heterogeneities which may have an important effect on dynamic properties.

These conclusions may be generalized to other cases after few complementary studies.

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Nomenclature.

ROS	:	Remaining Oil Saturation
SOR	:	Residual Oil Saturation
Swi	:	initial water saturation
Ko(Swi)	:	oil permeability at Swi
krw	:	water relative permeability
kro	:	oil relative permeability
Pc	:	capillary pressure
Q	:	injection rate
ΔP	:	pressure drop
F.S.	:	Full Size (abbreviation used on figures)
V.P.	:	Vertical Plug (abbreviation used on figures)
H.P.	:	Horizontal Plug (abbreviation used on figures)

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	Full size			Vertical plug			Horizontal plug		
Core sample characteristics									
Length (cm)	20.4			8.52			8.51		
Section (cm^2)	78.54			19.56			19.56		
Porosity (%)	22.4			21.6			18.8		
Swi (%)	23.8			27.7			28.3		
Ko(Swi) (mD)	75			110			175		
Experimental conditions									
Temperature (°C)	20			20			20		
Confining pressure (bar)	150			70			70		
Oil in place	Marcol 52			Marcol 52			Marcol 52		
Fluid properties									
Oil viscosity (cPo)	11.5			11.5			11.5		
Oil density	0.821			0.821			0.821		
Brine salinity (g/l)	20 (NaCl)			70 ($BaCl_2$)			70 ($BaCl_2$)		
Brine visco. (cPo)	1.0329			1.1156			1.1156		
Brine density	1.0123			1.0327			1.0327		
Viscosity ratio	11.13			10.3			10.3		
Waterfloods results									
Q (cm^3/h)	108	189	- (*)	24	53.8	90.8	24	53.8	90.8
ΔP (bar)	0.84	0.92	1.5 (*)	0.162	0.330	0.532	0.067	0.138	0.219
Filtration velocity (cm/day)	33.0	56.5	- (*)	29.5	66.0	111.4	29.5	66.0	111.4
Average front velocity (cm/day)	372	491.7	- (*)	278.2	613.6	1013.2	318.3	685.7	1128.7
Recovery (%OIP)	51.9	67.3	72.7	67.7	68.8	70.4	68.7	71.4	73.1
ROS (%)	36.6	24.9	20.8	23.3	22.5	21.4	22.4	20.5	19.2
krw (ROS)	0.127	0.204	0.256	0.182	0.200	0.210	0.275	0.300	0.320

(*) the last step of the full size experiment was carried out with a constant pressure drop

Table 1 : Main experimental results

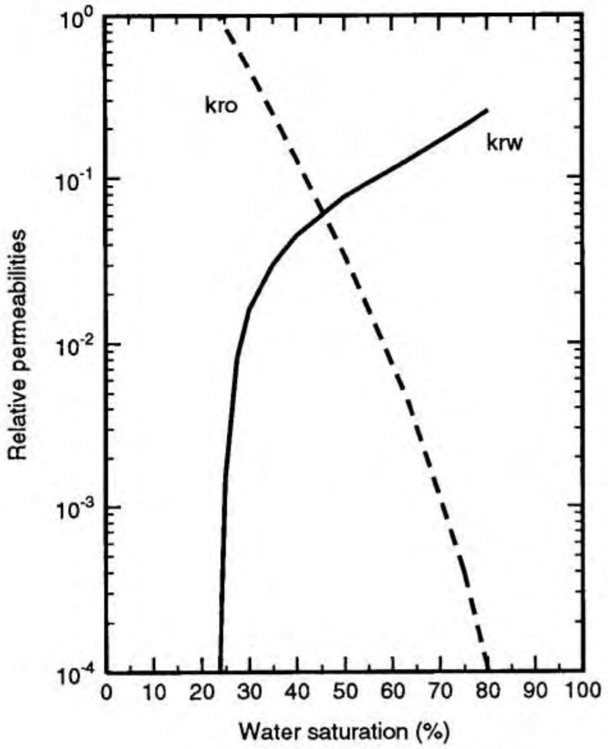

Fig. 1 : kr from the full size

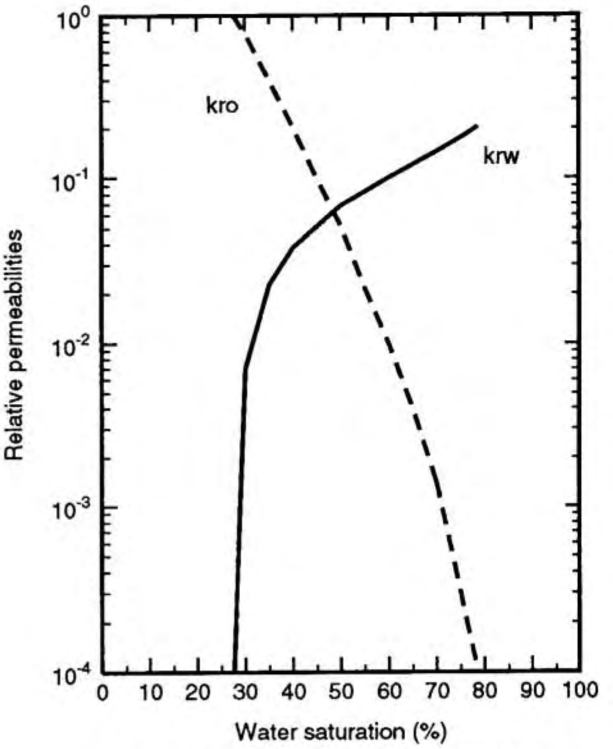

Fig. 2 : kr from the vertical plug

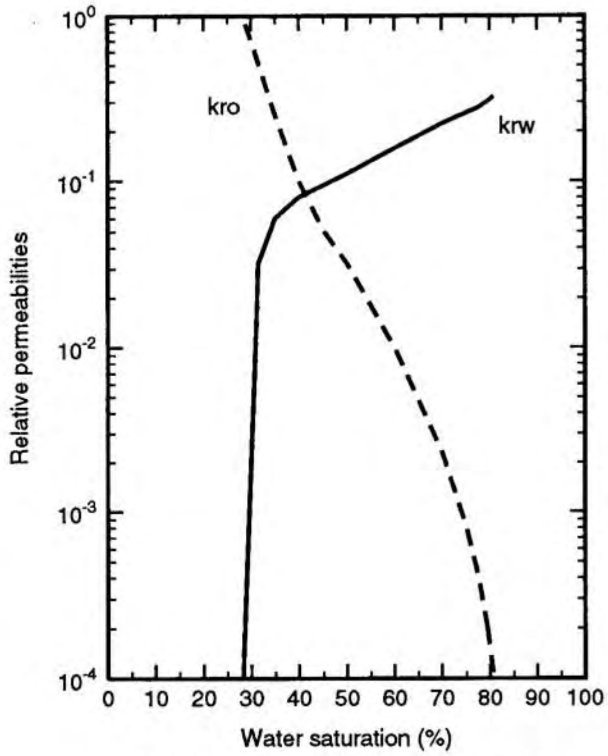

Fig. 3 : kr from the horizontal plug

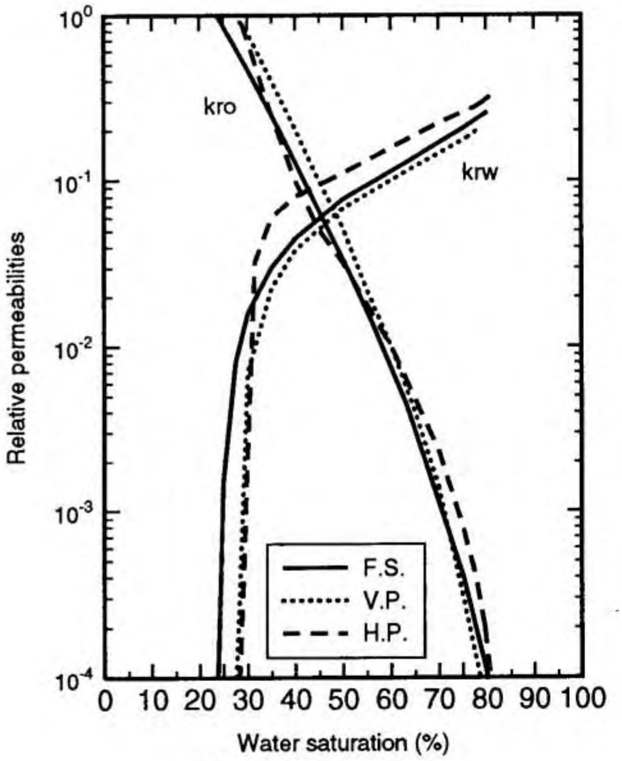

Fig. 4 : kr comparison

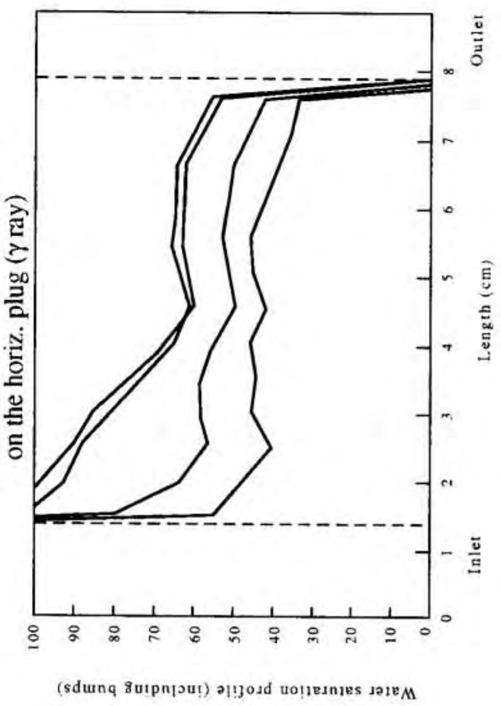

Fig. 10 : Water sat. profiles on the horiz. plug (γ ray)

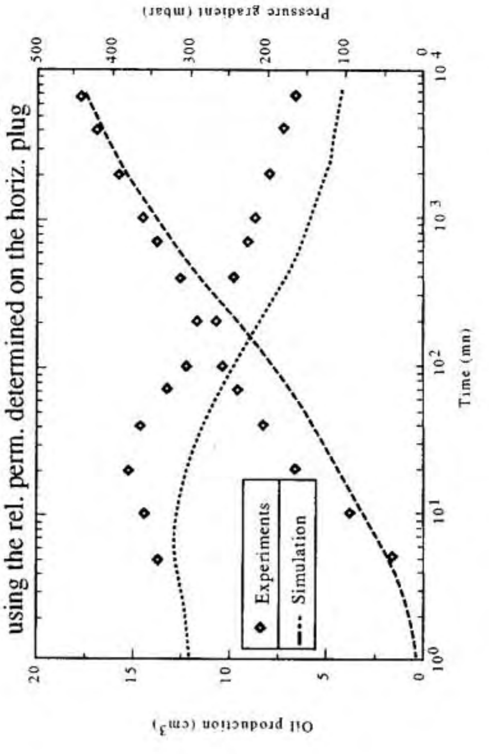

Fig. 12 : History matching of the vert. plug exp. using the rel. perm. determined on the horiz. plug

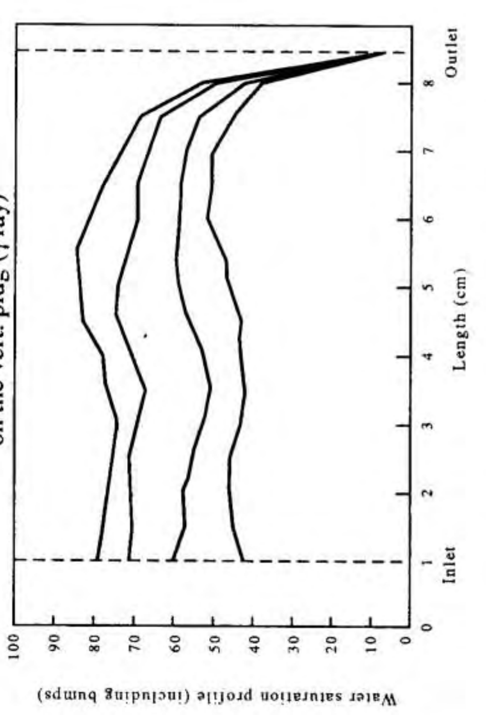

Fig. 9 : Water sat. profiles on the vert. plug (γ ray)

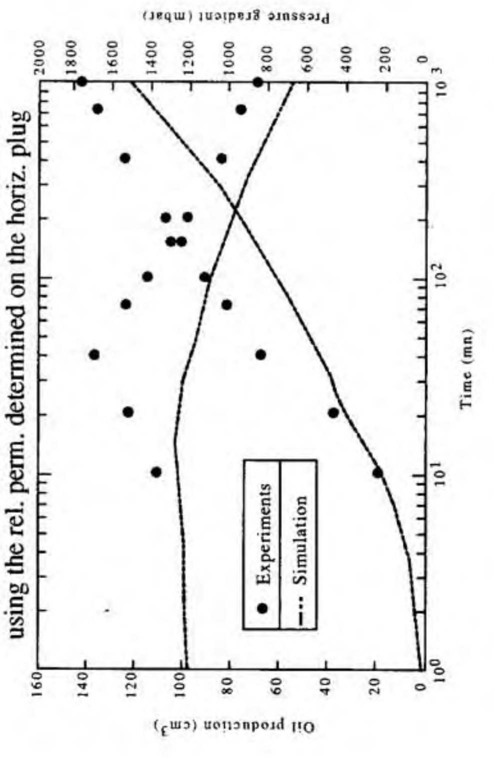

Fig. 11 : History matching of the full size exp. using the rel. perm. determined on the horiz. plug

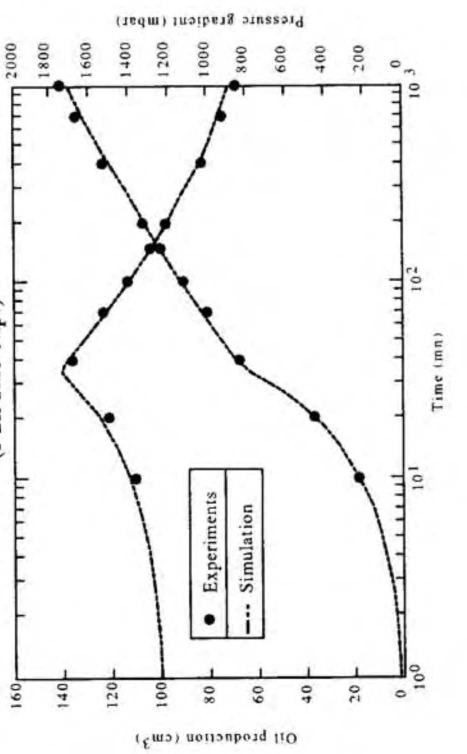

Fig. 5 : High rate waterflooding (Full size exp.)

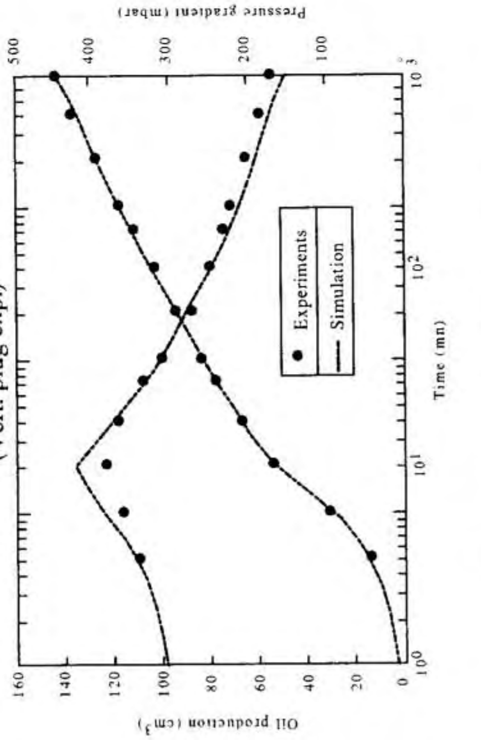

Fig. 6 : High rate waterflooding (Vert. plug exp.)

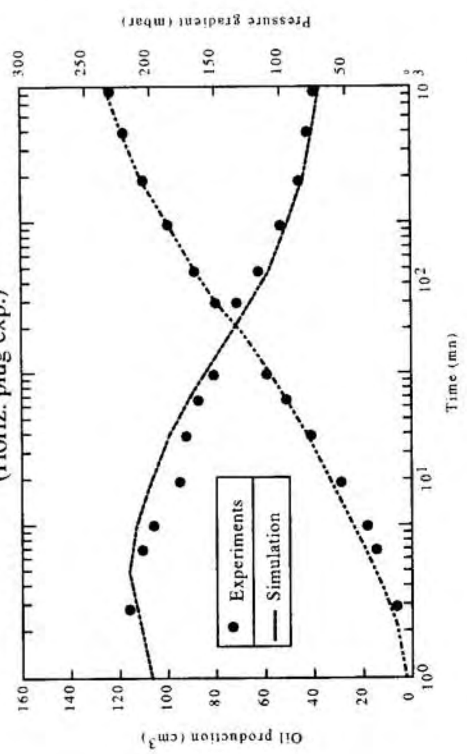

Fig. 7 : High rate waterflooding (Horiz. plug exp.)

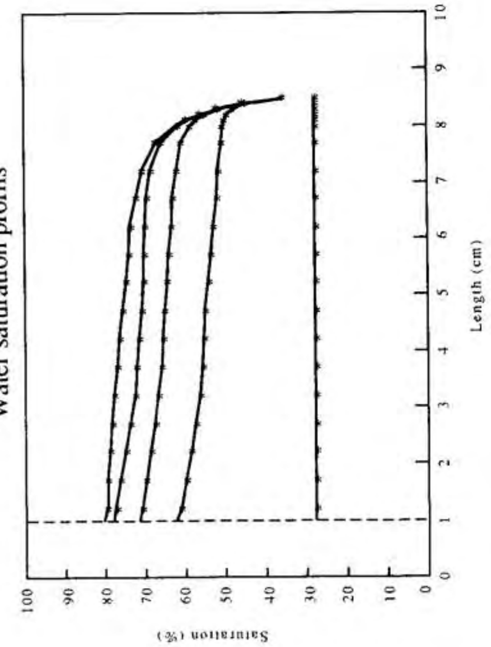

Fig. 8 : Numerical simulation (Vert. Plug) Water saturation profils