SPE 39657

Relative Permeability Curves: The Influence of Flow Direction and Heterogeneities. Dependence of End Point Saturations on Displacement Mechanisms

M. A. Crotti, SPE, Inlab S.A. and J. A. Rosbaco, SPE, ITBA

This paper was prepared for presentation at the 1998 SPE/DOE Improved Oil Recovery Symposium held in Tulsa, Oklahoma, 19–22 April 1998.

Abstract

This paper presents results that highlight some aspects not often considered when dealing with experimental relative permeability curves in heterogeneous media, a very common situation in natural sandstone samples.

When comparing curves obtained from the same core sample as a result of horizontal and vertical floodings, they show a large difference in residual oil values and in the general displacement performance. The information thus gathered indicates a systematic tendency towards notably lower residual oil in the case of vertical floodings.

These results are significant because of the large number of cases of vertical flooding occurring throughout the productive life of a reservoir, such as crossflow among strata of different permeabilities, predominantly segregate flow, expanding gas cap, flow from basal aquifers, etc. This is the reason for contesting the standard procedure of always using the same single set of relative permeability curves that, in practically all cases, are determined by horizontal flow.

Based on the results presented herein, it is suggested that the end points used in order to describe the different reservoir flow and production models be obtained using horizontal and vertical flooding, as well as by imbibition and capillary pressure tests.

Introduction

Most of the basic data used by reservoir engineers are obtained experimentally in the lab. Some of these test results are widely accepted, while others are under question. Examples of both cases are porosity and relative permeability curves, respectively.

Porosity obtained in the lab is used in a number of calculations and correlations, as well as to fine-tune values obtained using other methodologies, such as logging. It is widely accepted that this information as obtained in the lab is generally representative.

On the other hand, the relative permeability curves do not share the same degree of acceptance and credibility. This is particularly serious because the estimation of reserves in natural processes and in EOR projects using inmiscible fluids (water, gas, steam) heavily depends on relative permeabilities.

Although there is abundant literature on this subject, many experimental aspects of these curves, as well as their application in Reservoir Engineering, are debatable and controversial. The use of laboratory results during the numerical simulation stage is usually difficult and subject to ongoing revisions and changes. Usually, the origin of these difficulties is attributed to the little representativity of the samples. One other possible cause, rarely considered, is the intrinsic correctness of the tests and their ability to reflect what actually occurs in the reservoir. These qualities may also explain the apparent difficulty that is generally encountered when attempting a systematization of the relative permeability data derived from different samples and/or laboratories.

The primary purpose of this paper is to discuss aspects related to this latter cause. In order to fully understand the basic question, it is necessary first to point out a series of facts which are not usually fully considered when evaluating the lab data.

- Nearly all the samples analyzed are heterogeneous, as indicated by numerous publications[1,2]. Laminations visible to the naked eye are very frequent in sandstones. On the other hand, the use of micropermeameters confirms that it is very common that heterogeneities visible in well logs manifest themselves even at lab sample scale. It is a known fact that a second sample, even if taken as close to the first sample as possible, never reproduces the permeability and porosity data of the first sample.
- Nearly all equations and models used in the evaluation of flow tests presume the occurrence of homogeneous poral systems. Such an assumption becomes important in light of the previous statement.
- Most of the relative permeability measurements are performed through the unsteady state method, by which the re-

ported end points correspond to steady state flow conditions (homogeneous saturation and single phase flow), while the intermediate values are calculated during a transient stage in which sample saturation is not homogeneous. Because of this, the end point saturations should have greater validity than the remaining points in the curve, since the shape of the curves in heterogeneous systems depends - among other things - on the mobility ratio, while it is generally accepted that the end points - if properly extrapolated at the end of the test - are independent from it.

- It is generally believed that residual oil saturation, S_{or}, is obtained only after injecting "infinite" poral volumes of water. However, S_{or} can also be achieved through capillary/ gravitational equilibrium that depends solely on time. In the reservoir, the times involved are much larger than those employed in the lab.
- Although there are different ways of reaching the end points, as stated before, they tend to be numerically different depending on whether they come from capillary pressure tests or from relative permeability tests.
- Measurement of end point saturations depends on the interpretations and assumptions of the lab technician. In the case of S_{or}, the technician must extrapolate the production data[3] until "infinite" poral volumes of water are injected. This extrapolation usually is not valid for heterogeneous media, where the production curves show inflections derived from the different productivity and response time of different layers. For this reason, extrapolation leads to different values for S_{or}, depending on the time selected for ending the flooding. As is well known, there is currently no universal criterion for making the decision of when to end the test.
- Relative permeability curves in the lab include only the effect of the viscous forces, since the measurements and computations are performed minimizing the contribution of capillary and gravitational forces. However, capillary as well as gravitational forces, as emphasized by L. Dake[4], are often the predominant forces at reservoir scale.

In addition to these observations, there is a series of known and accepted facts, rarely interconnected, either among themselves or with the above observations.

- When measured in the lab, relative permeability curves (or their end points) in general do not allow for reproducing reservoir behavior in the numerical simulation. In fact, the relative permeability curve is often used as a parameter to fine-tune the simulator.
- When correlating relative permeability curves with other reservoir parameters, or when trying to average these curves, the dispersions obtained are so large that, in many cases, it may be concluded that the correlation is of low representativity. Regrettably, these data are not usually included in published correlations. Therefore, the user may fail to take proper notice.
- The influence of different factors on the measurement and calculation of relative permeability curves, and on how to consider these factors in order to minimize errors, is the subject of continuous studies[5,6,7]. This indicates that not only are there many variables to consider, but also that there still is a long way to go before an accurate method for obtaining truly useful data can be established.

The Appendix includes some very specific items particularly associated with lab methodologies. They permit a more thorough comprehension of the influence the analyst's criteria and experimental methodology have over the information provided to the reservoir engineer.

In addition to all the facts mentioned above, there is also a reasonable doubt about whether the end point saturations are independent from the oil recovery mechanism (flooding in different directions, injection rates, gravitational segregation, etc.).

If the answer to this question were negative, that is, if for a porous medium with certain fluid characteristics the saturation of the immobile phases were dependent neither upon the mechanism nor the direction of the injection, improving the determination of end point saturations could be attempted by resorting to full diameter samples. These may provide a displaceable volume some twenty times larger than that provided by the commonly used horizontal “plugs”. This difference in sample volume would not only make the study more representative but also notably minimize the experimental error.

If, on the contrary, the answer to the question were affirmative, the determination of the end point saturations would have to be performed following the prevailing reservoir mechanisms. In the case of a predominant vertical flow (segregate flow, basal aquifers, gas caps, supply from less permeable strata to or from the more permeable ones, etc.) vertical samples would have to be used. In this case, full diameter samples would also be more representative.

Based on the above considerations, it would seem reasonable to conclude that, in order to properly characterize the reservoir, the different displacement mechanisms and flow directions should be studied to analyze their effect on the production curves used to determine the system relative permeabilities. Since this study can only be performed at a lab scale, it is advisable that the same sample and set of fluids be used in all cases in order to obtain data for comparison purposes.

In an attempt to provide an answer to the questions posed, as well as to try to improve the quality of the information provided to reservoir engineers, this paper deals with the influence of horizontal and vertical floodings on residual oil saturation, S_{or}, and on the general performance of the production curve resulting from the water injection lab tests. The results obtained are sufficiently surprising as to cast a shadow of doubt on the validity of some concepts and commonly accepted assumptions.

Description of Test

Three tests were performed in order to check the influence of flow direction on the production curves. A cubic sample obtained from different reservoirs as indicated in **Fig. 1** was used in each case. It was thus possible to analyze the results of water flooding in three different directions (**Fig. 2**), maintaining in all cases the same flow geometry and exactly the same natural porous medium.

This paper presents a discussion of the results obtained on one of the samples; however, the conclusions are applicable to all of the cases studied. There is additional information derived from tests - not yet ready for publication - which points to the fact that similar results are obtained when the phases displaced are water or gas.

The basic data of the sample are included in **Table 1**

The following operating sequence was followed for performing measurements:

1. A 70 mm cubic sample was obtained. This sample has a volume five times larger than the usual 38 mm samples.
2. Water, oil and salts were washed off the porous medium.
3. Aluminum plates with rubber spacers were set in place to replace side ends eliminated during cube extraction.
4. Porosity and permeability to gas, in the three directions of the sample, were measured.
5. The sample was saturated with formation water.
6. Absolute permeability to water following direction h1 was measured.
7. The sample was flooded with oil (following direction h1) until irreducible water saturation reached S_{iw}.
8. Effective permeability to oil at irreducible water saturation $k_o(S_{iw})$ was measured.
9. A displacement test by injecting water at a constant rate was performed until total injection reached ten poral volumes of water.
10. Effective permeability to water at residual oil saturation $k_w(S_{or})$ was measured.
11. Stages 7 and 8 were repeated. These measurements were always performed in the direction of h1 to guarantee that the system initial conditions were the same.
12. The sample was rotated to allow a different flood direction.
13. Stages 9 to 12 were repeated until the entire test sequence was completed.
14. Samples were washed to perform the volumetric balance.
15. Calculations were performed.

A summary of flood data is included in **Table 2**.

The following standard lab techniques were used in order to simplify the experimental procedure:

- Oil was replaced by a 15 cp. viscosity vaseline, to prevent piston-like flow displacement conditions. This allowed sufficient time to record measurements during two-phase flow.
- Formation water was replaced by synthetic water of similar composition.

Two different flow rates were employed in each flood direction. Measurements were performed cyclically (directions h1, h2, z, h1, h2, z) in order to prevent potential cumulative or variable systematic changes that could mask interpretation of results.

Interpretation of Results. Based on the comparison of the six production curves, obtained over the same sample, (**Fig. 3**), the following conclusions may be derived:

- There is a marked difference between the production curves derived from the horizontal and vertical floods. The four horizontal flooding curves show a marked similarity and are very different, both in quality and quantity, from those corresponding to the two vertical floods performed on the same sample. The differences are also noticeable in the relative permeability curves (**Fig. 4**).
- Different residual oil saturations were obtained for horizontal and vertical floods. Flooding was more efficient in the vertical than in the horizontal direction.

The dependence upon flow direction of only one of the end point saturations (S_{or}) was studied in order to limit the number of variables. However, as mentioned before, some additional studies currently under way indicate that also the determination of S_{iw} depends on the flow direction.

From Lab to Office. The different behavior recorded for vertical and horizontal displacements indicates the need to identify the different flow geometries occurring in the reservoir as soon as possible. This will allow the lab tests to be planned accordingly.

When an accurate, complete or adequate description of the flow geometries is not possible, the tests should be planned so as to obtain the most complete information possible. This will provide sufficient flexibility to perform future calculations and simulations that would take into account the effect of all the forces that may potentially occur in the reservoir (viscous, gravitational and capillary), as well as the different movement directions. As a matter of fact, and considering that in reservoir engineering there is never a final interpretation, it is advisable to extend the above recommendation to all reservoirs of commercial interest.

A thorough program should include:

- Horizontal floods, parallel to the stratification planes.
- Vertical floods, perpendicular to the stratification planes.
- Studies of the equilibrium between capillary pressure and gravitational forces. The use of a centrifuge is recommended, as it allows the performance of imbibition and drainage tests with relative ease.
- Imbibition tests. This mechanism becomes important for determining the S_{or} in those reservoirs where gravity is a force of fairly little relevance and where rock characteristics (very heterogeneous strata) or fluid characteristics (very viscous oils) lead to the formation of fingerings, thus making difficult the flooding by the action of the viscous forces.

One of the tasks of the reservoir engineer is to identify which values should be used in each zone of the reservoir. This should be based on the prevailing mechanisms considered for that region. The lab tests should be designed accordingly, so as to obtain the information under equivalent circumstances.

As pointed out in the following paragraphs, this stage is particularly important. Based on the above considerations, residual oil saturation for horizontal flooding is higher than for vertical flooding. For this reason, when crossflow or gravitational forces predominate in the reservoirs, displacement efficiencies calculated using the usual data are pessimistic, because in the history matching stage they are generally compensated through an overestimation of the areal efficiency. This procedure may lead to discarding potentially interesting infill well drilling projects.

Conclusions

1. In stratified systems, there is a marked difference among the production curves obtained using different flow directions. Vertical floods are more efficient than those parallel to the stratification plane.
2. Additional testing seems to indicate that different irreducible water saturation values are also obtained for vertical and horizontal floods.
3. Since the remaining oil saturations are lower with vertical flow than with horizontal flow, the calculated displacement efficiency, based on the usual data, will be pessimistic when crossflows or gravitational forces predominate in the reservoirs.

The Appendix includes a series of general recommendations associated with these primary conclusions.

Nomenclature

$h1$ = horizontal direction
$h2$ = horizontal direction (perpendicular to h1)
k = permeability, L^2, md
k_o = effective permeability to oil, L^2, md
$k_o(S_{iw})$ = effective permeability to oil @ irreducible water saturation, L^2, md
k_w = effective permeability to water, L^2, md
$k_w(S_{or})$ = effective permeability to water @ residual oil saturation, L^2, md
S_{iw} = irreducible water saturation
S_{or} = residual oil saturation
z = vertical direction

Acknowledgments

We thank Diego Tejada and Rafael Cobeñas for valuable discussions on the interpretations of results and Liliana Petruzela for her helpful review and corrections on original manuscript. Support for this project was provided by INLAB S.A., ITBA and Petrolera Argentina San Jorge S.A.

References

1. Huppler, H.D., “Numerical Investigation of the Effects of Core Heterogeneities on Waterflood Relative Permeabilities”, AIME (1970) **249**, 381.
2. Jakobsen, S.R., Ingsoy, P., Braun, T., Guo, Y., and Aga, M., “Assessing the Relative Permeability of Heterogeneous Reservoir Rock”, Paper SPE 28856, presented at European Petroleum Conference held in London, U.K., 25-27 Oct. 1994
3. Jones, S.C., and Roszelle, W.O., “Graphical Techniques for Determining Relative Permeability from Displacement Experiments”, *J. Pet Tech.* (May 1978) 807-817; *Trans.*, AIME, **265**
4. Dake L.P.: *The Practice of Reservoir Engineering*, Elsevier, (1994).
5. Geffen, T.M., Owens, W.W., Parrish, D.R., and Morse, R.A.: “Experimental Investigation of Factors Affecting Laboratory Relative Permeability Measurements”, *Trans.*, AIME (1951), **192**, 99.
6. Honarpour, M., Koederitz, L., and Harvey, A.H.: *Relative Permeability of Petroleum Reservoirs*, CRC Press, (1986).
7. Bennion, D.B., and Thomas, F.B.: “Recent Improvements in Experimental and Analytical Techniques for the Determination of Relative Permeability Data from Unsteady State Flow Experiments”, SPE 10th Technical Conference and Exposition, June 26-28, 1991.
8. Buckley, S.E., and Leverett, M.C.: “Mechanism of Fluid Displacement in Sands”, *Trans.*, AIME (1942) **146**, 107.
9. Welge, H.J.: “A Simplified Method for Computing Oil Recovery by Gas or Water Drive”, *Trans.*, AIME (1952) **195**,91.
10. Johnson, E.F., Bossler, D.P., and Naumann, V.O.: “Calculation of Relative Permeability from Displacement Experiments”, *Trans.*, AIME (1959) **216**, 370.
11. Archer, J.S., and Wong, S.W.: “Use of a Reservoir Simulator to Interpret Laboratory Waterflood Data”, SPEJ, (Dec., 1973), 343.
12. MacMillan, D.J.: “Automatic History Matching of Laboratory Corefloods to Obtain Relative Permeability Curves”, SPERE, (Feb., 1987), 85.
13. Sarma, H.K., and Bentsen, R.G., “A Study of the Impact of Instability on Relative Permeability and Capillary Pressure”, Journal of Petroleum Science and Engineering, 2 (1989) 311-330. Elsevier Science Publishers B.V., Amsterdam

Appendix - Relative Permeability Curves. General Considerations.

This appendix contains details of some aspects of laboratory measurements that are not indispensable for understanding the significance of the results presented herein. They are, however, useful when evaluating the information. A detailed analysis of these paragraphs, along with the cited bibliography, provides a view of the number of variables that have to be dealt with in order to obtain truly representative relative permeability curves when working with heterogeneous samples. This task should not be left entirely to the lab technician; lab results should be regularly matched against the rest of the information available to the reservoir engineers. The macroscopic vision should never be left aside when designing and evaluating lab tests. This becomes even more important when considering the different measurement and interpretation criteria, as well as the different characteristics among reservoirs.

Important observations regarding laboratory data. In many cases, the production curve, the residual oil saturation and the permeability to water - at such saturation - notably depend on the flow rate used during displacement[7]. Although laboratories take different steps to correct, or not, the measurements performed, they mostly fail to inform what flow rates were used in the lab or the range of application of the reported data.

The relative permeability curves presented by the labs are usually continuous along the entire saturation range between S_{iw} and S_{or}. This continuity is artificial and incompatible with the frontal displacement theory[8,9,10], and is usually obtained through either numerical simulations[7,11,12], unstable displacement[13], or simple extrapolations. For this reason, the zone inferred should not be used during viscous displacements.

In stratified water-wet systems (frequent in the lab), water saturations above irreducible water saturation are often obtained as a result of displacement tests with oil. This is due to the fact that flooding with the hydrocarbonate phase (non-wetting) is limited to flow rates that produce no damage to the porous medium. Under these conditions, the differential pressure between the phases might not exceed the capillary pressures of the less permeable layers. This characteristic could explain some cases of very permeable and porous rocks that exhibit high S_{iw} values during lab flooding.

Residual oil saturation depends on the water saturation existing at the start of the waterflooding test. This is due to the fact that the higher the proportion of the poral net occupied by oil, the higher the quantity of oil retained during displacement with water. Thus, when initiating displacement with a water saturation higher than S_{iw}, the obtained S_{or} will be lower than the correct value.

Laboratories rarely observe the viscosity ratio of the reservoir strictly, even if this is essential when dealing with non-homogeneous systems. In particular, and as is also pointed out by L. Dake[4], mobility ratios less than 1 (near piston-like displacement) are seldom used. When they are used, the implicit method of calculation is applied to artificially obtain a broader spectrum of mobile water saturations that is not representative of the system physical reality.

Methods for measuring relative permeability curves. The steady state method, although more time consuming and notably more expensive, is usually recommended for the following reasons:

- The results are unaffected by the heterogeneities of the system. In the case of stratified media, when reaching the stationary state no intercross flow occurs and the relative permeabilities obtained represent an average of the relative permeability of each layer. The unsteady state method produces transient states that are reflected in the "anomalous" relative permeability curves.
- The calculations are very simple. The Darcy law is the only operation that must be applied to each fluid. The saturation of the system is homogeneous.

However, the following facts are often left unmentioned:

- The use of long measurement times and large injection volumes may affect the results due to fluid interaction with the porous medium.
- In homogeneous media, measurements performed using the unsteady state method lead to the same results as the steady state methods do[8,9]. This is not true for heterogeneous systems, where the steady state method eliminates the influence of heterogeneities.
- If the samples are heterogeneous, such heterogeneity will be present in the reservoir bed and, therefore, the curves characteristic of homogeneous media lack any representativity.
- Stationary conditions do not occur in the reservoir.
- If viscous forces do not predominate in the reservoir, only the end points are useful for the reservoir engineer. And in both lab methods, the end points are obtained by injecting the displacing phase only.

It would seem from the above considerations that the results of the steady state method in no case enhance the information to be used by the reservoir engineer.

Methods for calculating relative permeability curves. Based on the preceding paragraphs, and considering that the unsteady state method is the most adequate one, the calculation methodology best suited for it should be analyzed. It is very important at this point to highlight two of the main reasons why the implicit calculation method (numerical simulation) is usually employed[7]:

- Smooth curves are always obtained.
- Curves spanning the entire range of saturations between S_{iw} and S_{or}, are always obtained, irrespective of the system mobility ratio.

These are, in fact, negative reasons, because:

- Real curves are not smooth in heterogeneous media, so that when applying this methodology to stratified media reality is masked.
- Numerical simulation, allowing all water saturations to be mobile, denies the existence of frontal displacement[8-10] and therefore leads to unrealistic fractional flow curves.

Additionally, the use of the implicit method that always produces "nice looking" curves, gives way to a less neat experiment. The explicit calculation method requires excellent experimental data in order to resolve the equation systems by using numeric adjustments and production curve derivatives. Although the first reasons expressed are more valid, even if the latter were the only difference between both methods it would be sufficient to discard the implicit method, since it is always preferable to use a calculation methodology that requires improving the experimental quality of measurements.

It should also be pointed out that when using the implicit method for calculation, the S_{or} must be fed to a numerical simulator[7], therefore becoming a parameter affecting the entire shape of the reported curve. The explicit method of calculation is free of this dependency.

An excellent example of how the implicit method permits the introduction of alterations into the experimental data is found in the MacMillan paper[12], where in order to better adjust the experimental data, by using parameterized curves, the S_{or} is varied by some 15 percentage units of saturation, with no experimental evidence to support such change.

Intrinsic differences between lab studies and actual reservoir phenomena. The following facts should be considered when transferring the data from the lab to the reservoir, or when designing the studies to be carried out.

- When the end point saturations are obtained by displacement (viscous drive), virtually "infinite" poral volumes must be injected. This process can be performed in the lab, but not in the reservoir.
- When the end point saturations are obtained through equilibrium between the capillary forces and the gravitational forces, only one volume of water for each volume of oil displaced is required. This equilibrium depends on time and not on the volumes injected. In this case, very extended times can be obtained in the reservoir but not in the lab.

- Each system variable can be studied in the lab in a nearly independent manner, while in the reservoir it is only possible to record the joint effect of all the phenomena involved. As a result of this, it is strongly recommended to initially use very simple lab methodologies in order to study each phenomenon independently, and keep the use of complex equipment and work conditions for a later moment, when all the variables have been analyzed individually. In other words, simple and independent experiments should be the starting point, not floods in reservoir conditions with reservoir fluids, where all the forces and phase equilibria occurring in the reservoir are present.

Recommendations.

The following is recommended for measuring relative permeability curves:

- Use full diameter samples every time the study zone has predominant vertical flow (segregate flow, cross-flow to or from less permeable strata, etc.).
- Request laboratories to employ the viscosity ratio prevailing in the reservoir.
- Since the lab relative permeability curves include interpretation stages, the labs should be requested to provide the experimental data with no data preprocessing (raw data). Thus, the information obtained can be reinterpreted as required.
- The steady state method should not be used for measuring relative permeability curves. In no case does it seem adequate for representing actual reservoir conditions.
- Use the explicit method of calculation, since it is the only one that highlights the heterogeneities of the system. This information is quite useful when interpreting the whole lot of available data.

The following is recommended for measuring the end points:

- Use all the mechanisms indicated: horizontal flows, vertical flows, imbibition measurements and capillary pressure measurements.
- Extrapolate the final values based on the production curve. The end point saturations can not be accurately obtained without extrapolating the trend of the production curves obtained in the flood tests. Under no circumstances should only end point saturations be requested from the labs. End point values should always come with the relative permeability curve in order to evaluate data quality and representativity.

The following is recommended for moving lab data onto reservoir:

- The relative permeability curves should not be averaged algebraically. Under no circumstance is this a recommendable practice. Only the pseudo-functions have physical meaning, and these depend not only on the lab curves (viscous flow) but also on strata geometry, vertical communication, production rates, etc.
- The use of end point saturations rather than the complete relative permeability curves should be emphasized for most cases. As previously mentioned, this should not be interpreted as meaning that the entire relative permeability curve should not be determined. Complete curves are fundamental to provide higher accuracy to end point values. Additionally, the entire curve will indicate whether there are heterogeneities in the system and/or if damage has occurred in the sample during the experiment.
- The end point saturations obtained through the different ways proposed should be analyzed and compared.
- The prevailing production mechanisms in the different reservoir areas should be identified in order to obtain the information from the most representative tests.

SI Metric Conversion Factor

cp. x 1.0 E - 03 = Pa.S
in. x 2.54 E + 00 = cm
in.^{3} x 1.6387 E + 01 = cm^3
md x 9.869 233 E – 04 = μm^2

TABLE 1 – CUBIC SAMPLE and FLUID PROPERTIES

Bulk Volume, cm^3	343.0
Porosity, %	15.5
Poral Volume, cm^3	53.17
kh1, md	9.43
kh2, md	9.14
kz, md	2.72
Lithology	Laminated Sandstone
Oil Viscosity, cp.	14.4
Water Viscosity, cp.	1.03

TABLE 2 – MULTI-DIRECTIONAL FLOW RESULTS

Flow Direction	Flow Rate [cm^3/seg]	S_{iw} [% PV]	k_o (S_{iw}) [md]	k_w (S_{or}) [md]	**Oil Recup. [%OOIP]**
h1	4.0	24.0	5.43	0.564	**60.7**
h1	2.0	24.0	4.85	0.417	**61.9**
h2	4.0	24.0	3.82	0.362	**60.0**
h2	2.0	24.0	3.65	0.355	**60.7**
z	2.0	24.0	1.21	0.106	**68.8**
z	1.0	24.0	1.10	0.099	**70.5**

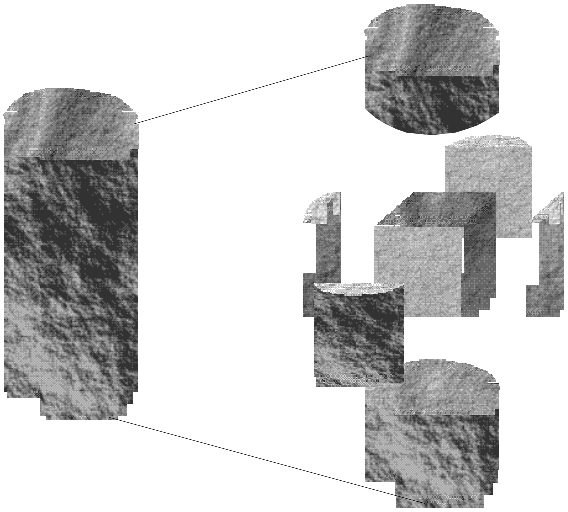

Fig. 1. – Schematic of cubic sample extraction from a whole diameter core.

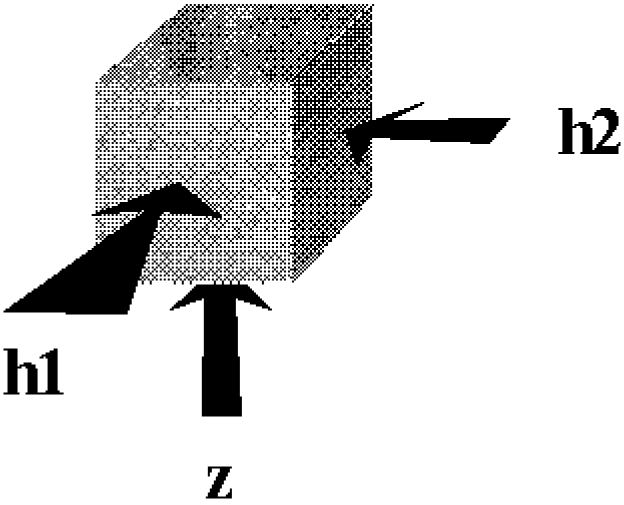

Fig. 2. – Flow directions during waterflooding of cubic sample.

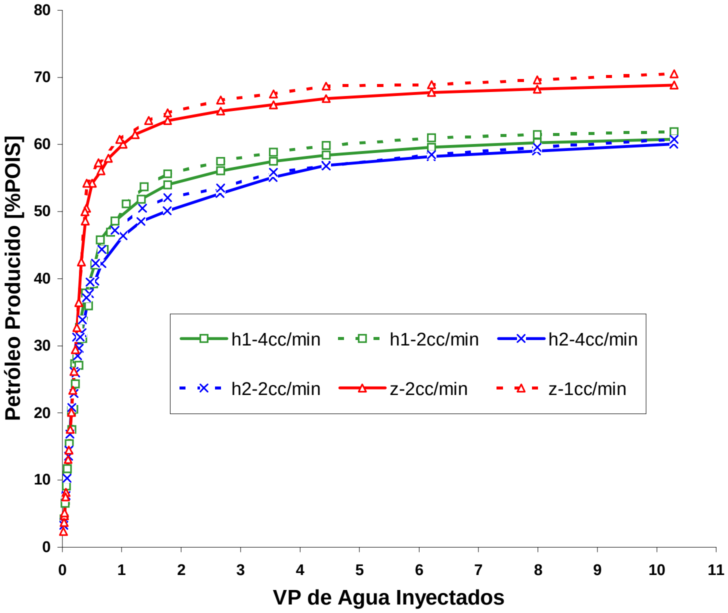

Fig. 3 - Effect of flow direction on oil recovery during waterflooding

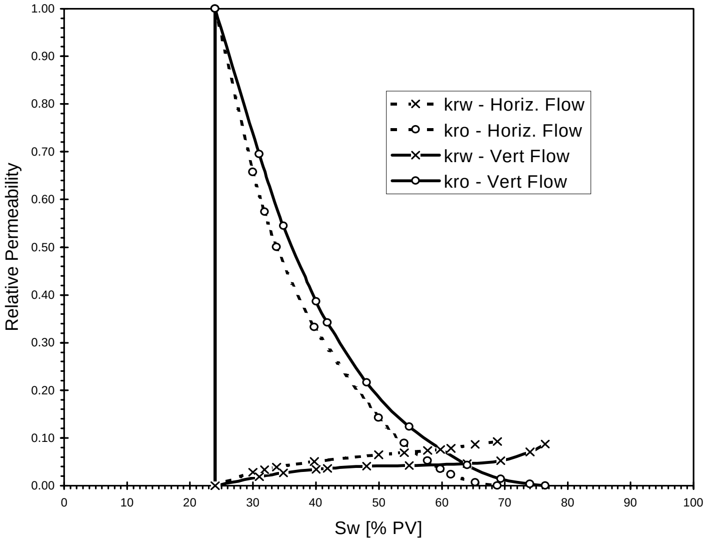

Fig. 4 - Effect of flow direction on water-oil relative permeability curves