THE SPINNING POROUS PLATE (SPP) METHOD: A NEW TECHNIQUE FOR SETTING IRREDUCIBLE WATER SATURATION ON CORE SAMPLES

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ABSTRACT

In special core analysis programs, setting a representative initial water saturation is essential. Many properties, such as wettability, oil residual, capillary pressure and relative permeability curves, depend on that initial saturation. We propose an efficient technique combining centrifuge and porous plate to reach low water saturation in a reasonable amount of time.

There are essentially two techniques to set initial water saturation: (i) flooding using a viscous oil and (ii) quasi-static displacement using for example the porous plate technique. Assuming homogeneous samples, the first technique is relatively fast and easy to implement but low water saturations are difficult to reach and a non-uniform saturation profile often results which can yield ambiguous results. The second technique produces a uniform saturation profile but is time consuming and depends on the quality of the capillary contact between the sample and the porous plate. Centrifuge desaturation is very fast but is usually avoided because of an non uniform profile which includes a weakly or not desaturated region at one face of the sample.

The proposed method combines the advantage of the porous plate (uniform saturation profile) and the advantage of the centrifuge (speed). A sample is simply placed on a porous plate and centrifuged. However, the porous plate is perforated to allow a fast drainage of the fluid contained in the sample, while the capillary foot is still eliminated. The breakthrough pressure of the porous plate is also properly adjusted to avoid desaturation and inaccurate saturation measurements. We show experimentally and theoretically how the system should be designed for a given capillary pressure. The elimination of the capillary foot is demonstrated using X-ray CT scans. The effect of the porous plate perforations is also studied (kinetics, boundary condition).

INTRODUCTION

In special core analysis programs, setting a representative initial water saturation is a key factor when preparing samples. Typically, if one wants to study the efficiency of water flooding and measure capillary pressure and relative permeability curves, the initial saturation, S_{wi}, is important and must be representative of in situ conditions. The term 'initial' is used here on purpose to avoid any confusion with the term 'irreducible' describing the asymptotic saturation obtained at high capillary pressure for a given set of fluids – in a transition zone, these two saturations are very different. The method presented here is efficient at producing irreducible saturations at high capillary pressures. The residual oil saturation, S_{or}, depends on S_{wi} and more importantly, the wettability will depend on the amount of water present in the pore system.

In the standard procedure, plug samples are cored from the full-size samples, then cleaned with appropriate solvents to obtain a wettability representative of the one present originally in the reservoir before oil migration (*i.e.* a water wet condition). Then, the sample is set to initial S_{wi} or S_{wirr} water saturation according to its location in terms of capillary pressure and aged with crude oil. At that point, the amount of water present is a key factor to obtain a representative wettability state. Therefore, a significant effort is usually made for the S_{wi} setting, and it can take a significant amount of time when using traditional techniques such as viscous oil injection or porous plate desaturation. Although centrifuge desaturation is the most efficient technique to desaturate samples, it has not been used for S_{wi} setting because of the presence of a strong saturation profile which may generate interpretation problems when performing subsequent flooding experiments. As an alternate technique, one should mention the drying method, in which the great difficulty is to control or impose the salinity and the saturation profile. Ideally, one would like to use a displacement process dominated by capillarity, as in situ, with experimental time compatible with the schedule of the field development or reassessment program, which is usually short.

We will briefly review the advantages and drawbacks of the traditional methods. Then we present the proposed methodology based on a combination of porous plate and centrifuge. To validate the technique, we performed X-ray CT scans to show the uniformity of the saturation profile and we compared the kinetics of the system with a standard experiment. We consider also some specific aspects concerning the pressure boundary conditions.

BACKGROUND

The most common method used to desaturate a sample is the injection of a viscous oil (typically 50 cp). This method is convenient because the sample is mounted in the cell used later for the flooding process. However, it is well known that low water saturations are difficult to reach, mainly because of the presence of heterogeneity at all scales, despite the use of a viscous oil. For low permeability, a viscous oil can also be impractical because the average saturation can still be high after breakthrough and the tail production can take several days. Moreover, the saturation profile is strongly non-uniform, in a similar way as the standard centrifuge method (see below). This profile can however be reduced by reversing the injection direction.

To avoid non-uniform profiles and reach low water saturations, the porous plate method can be used. The experiments are highly time consuming (of the order of months), especially when long samples are considered. Moreover, the capillary contact between the sample and the porous plate is often difficult to maintain and can result in a low success rate.

Finally, the centrifuge technique is probably the most attractive solution. It is a fast and low cost, capillary dominated displacement process with several practical advantages: easy manipulation, accurate pressure control. However, a major drawback is the non-uniformity of the saturation profile and for some centrifuges, a limitation in the sample length.

METHODOLOGY

Principle

The principle of the new spinning porous plate (SPP) method, assuming a drainage process, is shown schematically in Figure 1. A sample of length L is centrifuged on top of a perforated, thick porous ceramic of length t. The ceramic allows the saturation profile to be quasi-uniform (removal of the capillary foot) as in the porous plate technique and the perforations allow the highest possible flow rate to be maintained during centrifugation. Note that the removal of the capillary foot has been considered several times in the past to allow simplification of the analysis of centrifuge data (*e.g.*, Ragazzini *et al.*, 1992). Recently, a similar method was used to avoid strongly non-uniform profiles in the context of resistivity measurements (CRIM method, Han *et al.*, 2007).

Ignoring any two dimensional effects, the capillary pressure at a radius r is given by:

$$Pc(r) = \frac{1}{2}\omega^2 \Delta\rho (R_{\max}^2 - r^2)$$ (1)

where $\Delta\rho$ is the density difference between water and air (or oil) and ω is the speed of rotation of the centrifuge. Assuming a capillary contact between the sample and the ceramic, equation 1 indicates simply that the capillary pressure at the sample outlet face is different from zero, and therefore, the outlet face of the sample will be desaturated.
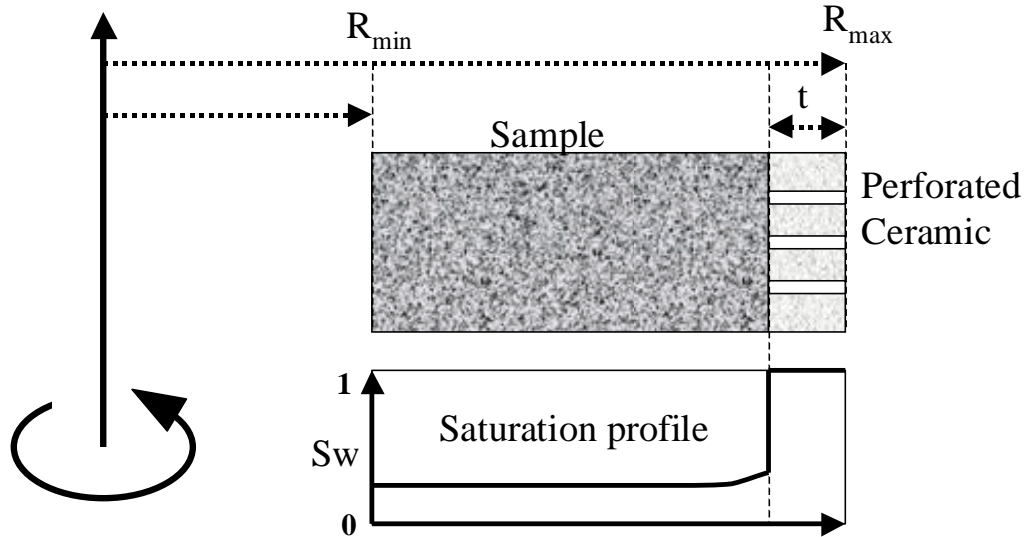
Figure 1: Principle of the proposed method: a perforated ceramic is added to the bottom of the sample. In the present design, there are about 20 perforations of diameter 2 mm.

From eq. 1, we can express the ratio of capillary pressure at the sample inlet $P_c(R_{min})$ and outlet $P_c(R_{max}$-$t)$:

$$\frac{Pc_{\,inlet}}{Pc_{\,outlet}} \;=\; \frac{R_{max}^2 - R_{min}^2}{R_{max}^2 - (R_{max}\text{-}t)^2} \tag{2}$$

Typically, the ceramic thickness is 1 *cm* and the above ratio will be 6.1 and 8.7 respectively for L=6 and 10 *cm* respectively (R_{max}=25 *cm*). For a given capillary pressure curve, this ratio expresses indirectly the minimum and maximum saturation in the sample.

To illustrate the effect of the ceramic, we calculated the saturation profiles at different speeds of rotation with and without ceramic for a measured capillary pressure (Figure 2, S_w=f(P_c) and P_c=f(r) from eq. 1). When the speed of rotation is sufficient, the saturation profile is nearly constant because all of the sample is at a pressure corresponding to the asymptotic part of the P_c curve. Further discussion of these results is made in the section 'Practical aspects'.
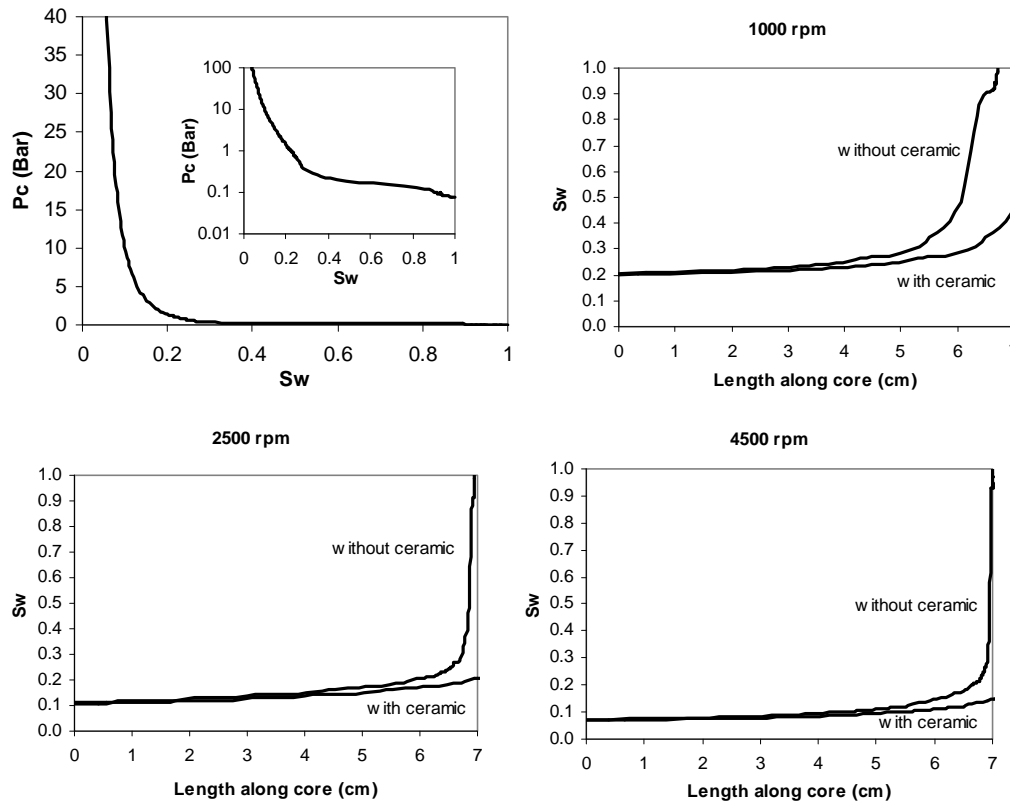
Figure 2: Examples of saturation profiles calculated with and without ceramic (air-water system). The capillary pressure was deduced from mercury injection. Due to the ceramic, the S_w profile is nearly uniform at high speed (>2500 rpm). The inlet face is located at a radius R_{min}=17 cm (x=0 along core).

Effect of the perforations, boundary conditions

First, the ceramic is build such as to have an entry pressure above the highest capillary pressure at the radius $r=R_{max}-t$. It is therefore never desaturated. A desaturation of the ceramic would lower considerably the flow rate (relative permeability effect), add uncertainties in the mass balance for saturation calculation, and potentially would not facilitate a good capillary contact. In the present case, the air-water entry pressure of the ceramic is about 3.5 *Bar*. The draw-back is that its permeability is small (K_c≈0.2 mD). Hence, if not perforated, the flow rate would be dominated by the ceramic as predicted by the equation:

$$\frac{L+t}{K_T} = \frac{L}{K_s} + \frac{t}{K_c} \tag{3}$$

For example, for a sample of permeability K_s =100 mD, the total permeability K_T would be 1.2 mD, a considerable loss.
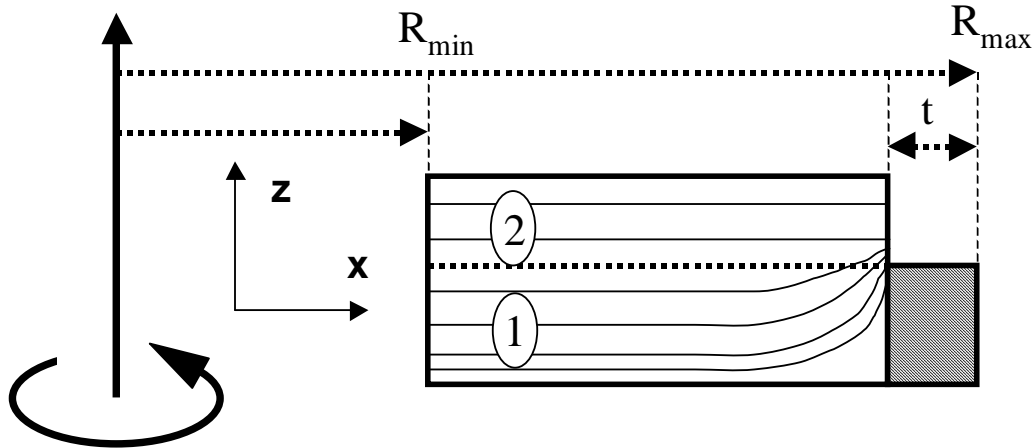
Figure 3: Effect of the perforations. The dashed zone indicates a ceramic. The sample is divided into two regions of different capillary pressure. Region 1 represents schematically the part of the sample that contacts the ceramic disc while Region 2 represents schematically the part of the sample that contacts a perforation (for simplicity only one perforation is represented). The thin lines indicate the flow lines.

The perforations allow the kinetics of the system to be dominated by the sample and not by the ceramic (see the section "Experiments"). However, the question arises as to the boundary conditions and this is not totally straightforward. To demonstrate that the perforations do not modify the capillary pressure at the outlet face, we consider the system shown in Figure 3. Above a perforation (region 2) and above the ceramic (region 1), the capillary pressures are in vertical equilibrium according to:

$$P_{C1} \ (r) \ = \ \frac{1}{2} \ \omega^2 \ \varDelta\varDelta\rho \ (^2_{max} - r^2) \ \text{and} \ P_{C2} \ (r) \ = \ \frac{1}{2} \ \omega^2 \ \varDelta\varDelta\rho \ ((_{max}\text{-}t)^2 - r^2) \ + \ C \ (4)$$

where *C* is an unknown integration constant. At a given r, a difference of capillary pressure in Regions 1 and 2 would induce a flow that cannot be balanced by any forces in the *x*-direction. Therefore, to achieve equilibrium in the *x*-direction, P_{c1} and P_{c2} must be equal and the saturation in Regions 1 and 2 must be equal. In particular, at the outlet face of the sample where no ceramic is present (Region 2), a desaturation also occurs.
The above arguments are very similar to the one developed by O'Meara *et al*. (1992) in their discussion of the outflow boundary condition and the perturbations caused by the wettability of the end-piece support. In practice, the perforations should not be too large (size of Region 2 too large compared to Region 1). For mechanical constraint, the diameter of the perforations is 2 *mm* and their number has been set empirically to 20 (hence the average distance between perforations is about 0.8 *cm*). Most of the fluid expelled from the sample will flow through these perforations. Further discussion is made in section Experiments.

Practical aspects

In practice, there are several advantages of the SPP technique:
- the manipulation is simple and many samples can be desaturated at once (6 in our case); using large radius centrifuges (R_{max}=25 cm) and with intermediate speed (ω_{max}=4900 *rpm*), the sample length can be as large as 12 *cm* and high capillary pressure can be reached (64 *Bar* for air/water, 31 *Bar* for dodecane/water),
- the capillary contact is easy to obtain (if the sample faces are flat) because the centrifugal forces push the sample onto the ceramic,

The main difficulty is to not damage the sample, especially for long ones. Hence, it may sometimes not be possible to obtain a uniform saturation profile when the speed of rotation must be limited. There are two solutions to get around this problem: (i) use a longer ceramic to decrease the ratio of $P_{c\ inlet}/P_{c\ outlet}$ (eq. 2) and minimize the speed of rotation and/or (ii) invert the sample and spin a second time at low speed for a similar amount of time.

The method can be applied equally well to air/water drainage or oil/water drainage. The air water drainage has however some advantages compared to oil. First, because the density difference is larger, a lower speed is necessary with less potential damage to the sample. Second, the air/water desaturated sample is easier to install in a flooding cell for further experiments. Air can be replaced by oil using a sequence of miscible displacement of C1, cyclohexane, and crude oil. Third, the calculation of saturation is more precise. As an IFP standard procedure, three measurements are performed to estimate the final average saturation: a measure of the volume expelled from the sample, a measure of the sample weight (for grain loss estimates) and an NMR measurement (before and after centrifugation). The later allows also the establishment of a database useful for other purposes.

Experiments

Several experiments have been performed to show the validity of the proposed method. First, we verified the effect of the ceramic on the saturation profiles. Second, we consider the kinetics of the desaturation process with and without ceramic.

CT scan saturation profiles

Saturation profiles have been measured on two samples, one sandstone and one carbonate, with and without ceramic as the end-piece support (two experiments performed sequentially, the samples being resaturated at 100% in between). The effect of the ceramic is clearly seen at low and intermediate speed (Figure 4) for the sandstone. At high speed, the experiment without ceramic may seem to give a uniform profile but this is due to a lack of resolution of the CT scan. With ceramic, we are confident that the profile is truly uniform. For the tight carbonate also shown in Figure 4, the profiles at low speed are similar because the spinning time was short (6hrs). At the highest speed, the difference is obvious. However, the profile in the presence of the ceramic is not totally uniform. In these cases, one should typically invert the sample and centrifuge it further. For both samples, typical spinning time was between 24 and 48 hours.
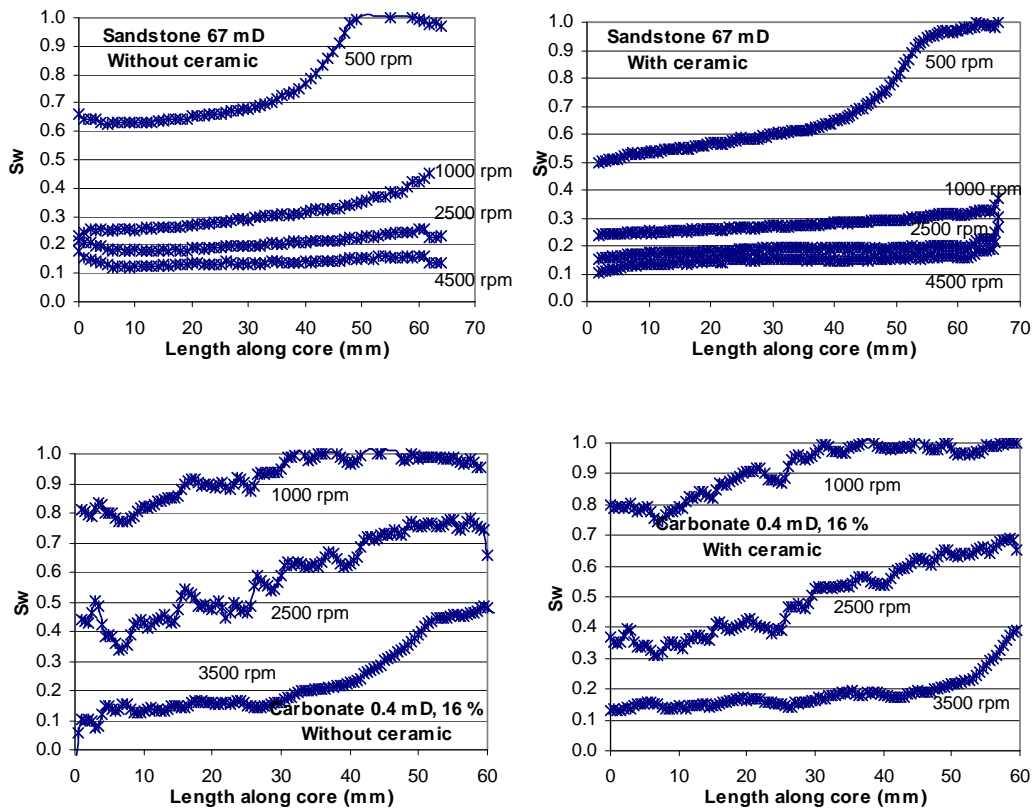

Figure 4: X-ray CT scan of one sandstone and one carbonate at different speed of rotation with and without ceramic. For the sandstone, the final saturation profile is uniform. For the tight carbonate, a profile is still present and the sample should be inverted and centrifuged further.

Kinetics with and without perforated porous plate

We tested the kinetics of the desaturation process with and without ceramic. As explained above, the perforations should not modify significantly the flow rate. This is clearly seen when comparing the transient saturation when centrifuging two companion plugs of medium permeability (about 180 *mD*, note that one plug was shortened to produce   a similar pressure drop). A low saturation is reached within hours in both cases.
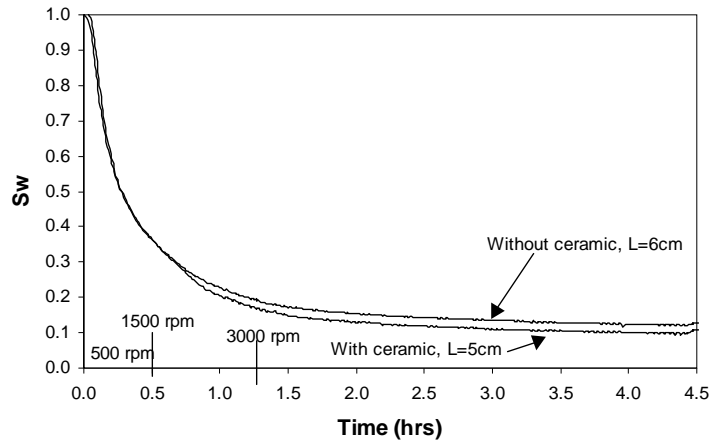

Figure 5: Comparison of the transient production with and without ceramic on two companion plugs (air/water). The speed of rotation was set initially to 500 *rpm* (*t*=0), then to 1500 *rpm* (*t*=0.5 *hr*) and 3000 *rpm* (1.25 *hr*). A low saturation is reached within hours with a capillary dominated displacement. The sample without ceramic had *L*=6 *cm*, K_w=194 *mD*; the sample with ceramic had L=5 *cm*, K_w=171 *mD*.

It is interesting to known the typical time necessary to drain the capillary foot only (Figure 6). In this experiment, a sandstone sample has been first centrifuged using the PWC technique (Fleury *et al*., 1998) and the oil-water level maintained continuously at the outlet face of the sample (R_{max}-*t*, Figure 1). At time 0 (Figure 6), the level was moved to R_{max} and the production measured. We observed that a stable saturation is reached within hours, and this time depends essentially on the ceramic, not the sample (hence this observation is also applicable to air/water drainage). The saturation stabilization is quite fast despite the low permeability of the ceramic because only a small fraction of the sample must be drained (roughly, a half sphere of diameter equal to the distance between the perforations).
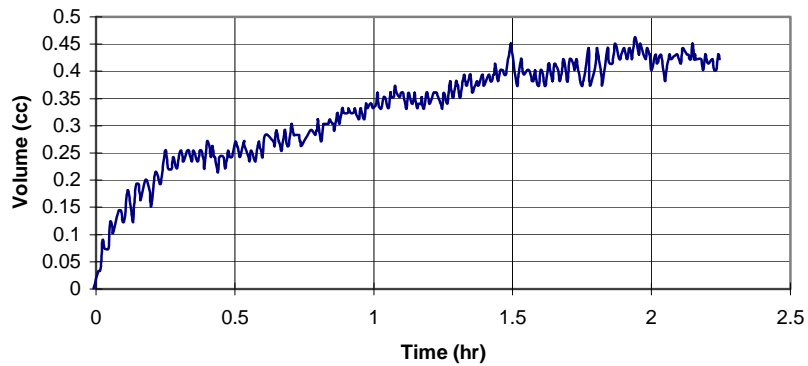
Figure 6 : Production observed when the oil-water level is moved rapidly from the outlet face of the sample (R_{max}-t, Figure 1) to the outlet face of the ceramic (R_{max}). Pumping While Centrifuging experiment, figure 7 of Fleury et al. (1999). Sandstone sample: K=610 mD, ϕ=23%, L=5.9 cm, oil-water drainage.

In general, the spinning time depends on several parameters (length, capillary pressure, relative permeability of water at low saturation) and a precise prediction is difficult to make. Our experience indicates that even for tight formations, the target saturation can be reached within 48 hours.

CONCLUSIONS

We present an efficient technique for setting irreducible water saturation. The centrifuge-modified porous plate combination described here takes advantage of both techniques while eliminating their major draw-backs. For medium/high permeability (>10 *mD*) consolidated samples, a uniform profile is obtained while low water saturation can be reached within hours/days. For low to very low permeability, the saturation profiles are quasi-uniform. Thicker perforated ceramics should be used in these cases.

ACKNOWLEDGMENTS

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