DEVELOPMENTS IN CENTRIFUGE MEASUREMENTS OF RELATIVE PERMEABILITY AND CAPILLARY PRESSURE HYSTERESIS

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ABSTRACT

The determination of relative permeability and capillary pressure hysteresis by using the centrifuge is a challenging task and various techniques are presented in the literature. In the present work these two types of centrifuge measurements have been investigated with respect to laboratory procedure, theory and calculations.

The centrifuge technique for determination of relative permeability is based on the transient production data obtained during centrifuging with a constant revolution per minute (RPM). The main objective of this part of the study was to investigate the effect of the centrifuge start up time or acceleration period on the calculated relative permeabilities. The duration of the acceleration period depends on the final desired speed but will usually last 10 seconds or more for most commercial centrifuges. A water/air primary drainage process was performed on 10 Berea sandstone core plugs and a water/oil secondary drainage process was performed on two chalk core plugs. The results show that for the Berea sandstone with a permeability in the range of 400-500md the acceleration period has to be included in the calculation of the relative permeability. The relative permeability calculations of the low permeability chalk plugs (approx. 1 md) are not affected significantly by the centrifuge acceleration period.

The centrifuge technique for investigating capillary pressure hysteresis is based on the ”footbath” method, where the movement of the fluid/fluid contact level is recorded by an automatic video camera system. This technique has been shown by several authors to give reliable capillary hysteresis results (primary drainage and spontaneous imbibition) for strongly water wet core plugs. The main objective of this capillary hysteresis study was to evaluate the applicability of the ”footbath” technique when the capillary cycle starts with secondary drainage and proceeds with spontaneous imbibition. Four strongly water wet Berea sandstone core plugs and three chalk core plugs with variable wettability were used in the experimental program. The results show that in the case of weakly water wet core plugs the fluid exchange due to the negative (forced) capillary imbibition (occurring below the fluid/fluid contact level) is very significant and can introduce large errors in the calculated positive imbibition curve. The conclusion is therefore that the ”footbath” technique gives reliable capillary hysteresis results for very water wet rock samples but the technique should be examined carefully before being used for weakly water wet plugs. Only in the case of long plugs and low fluid/fluid contact level will this technique be reliable for weakly water-wet plugs.

INTRODUCTION

Relative permeability and capillary pressures are two of the most important parameters in reservoir engineering works. Multi-speed centrifuge experimental measurements can be used to calculate both the relative permeability and capillary pressure simultaneously by collecting the production data with time. With an automated centrifuge, the measurements are fast and easy to carry out. Some earlier developments regarding experimental techniques and theory are given in references 1–7. The relative permeability calculation method was derived from Hagoort[8] theory and the effect of the centrifuge acceleration period is investigated in detail. The capillary pressure calculation method was derived from Hassler and Brunner[9] theory. The applicability of the "footbath"-technique for studying capillary hysteresis was investigated.

Relative permeability. The theory developed by Hagoort[8] for calculating relative permeability from a centrifuge experiment where air is displacing water is as follows:

$$k_{rw}(S_{w2}^{*}) = \frac{dN_p}{dt_d} \quad (1)$$

and

$$N_p = 1 - S_{w2}^{*} + k_{rw}(S_{w2}^{*}) \cdot t_d \quad (2)$$

Where N_p is the cumulative water production expressed as a fraction of initial water volume in place, S_{w2}^{*} is the reduced water saturation near the core outlet and t_d is dimensionless time defined as:

$$t_d = \frac{k \cdot \Delta\rho \cdot R_m}{\mu \cdot \phi^{*} \cdot L} \int_0^t \omega^2(t) \cdot dt \quad (3)$$

where L is core length, k is air permeability, R_m is the distance from rotational axis to core center and ω is angular velocity. In the dimensionless time equation, the expression outside the integral sign is only dependent on rock, fluid and apparatus parameters and is constant:

$$C = \frac{k \cdot \Delta\rho \cdot R_m}{\mu \cdot \phi^{*} \cdot L} \quad (4)$$

The other part of Equation (3) is an integration of revolution with time. The revolution versus time is shown in Figure 1. It is observed that the revolution is transient until t_t and then reaches a stable situation. t_t is the centrifuge start up time or the acceleration period. It depends on the speed range but will usually last 10 seconds or more for most commercial centrifuges.

In this work the transient period of centrifuge revolution was determined for different speed ranges and we found an approximate linear relationship

$$\omega(t) = at + b \quad (5)$$

The integral in equation (3) will then be:

$$\int_0^t \omega^2(t)dt = \frac{a^2}{3} t_t^3 + abt_t^2 + b^2 t_t + \omega^2 \cdot (t - t_t) \quad (6)$$

By combining Equations (3) and (6) a more accurate dimensionless time is obtained and the effect of the acceleration period on relative permeability can be determined.

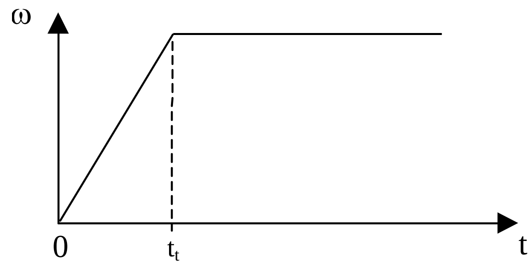

Figure 1: Revolution versus time

<u>Capillary pressure</u>. The capillary pressure versus water saturation was developed by the Hassler and Brunner[9] method.

$$p_{c1}(r_2) = \frac{1}{2} \Delta\rho \cdot \omega^2 \cdot (r_2^2 - r_1^2) \qquad (7)$$

$$S(p_{c1}) = \frac{d}{dp_{c1}} \cdot (p_{c1} \cdot \bar{S}(p_c)) \qquad (8)$$

Where $S(p_{c1})$ and p_{c1} is the water saturation and capillary pressure in the core inlet, respectively. $\bar{S}$ (p_c) is the average water saturation of the core.

In the capillary pressure hysteresis study the "footbath"-technique with movable water-oil-contact was used. Figure (2) shows the schematic drawing of the centrifuge core holder.

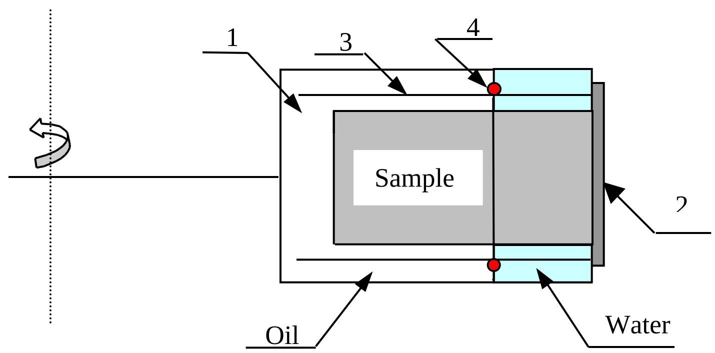

Figure 2: Schematic drawing of the centrifuge core holder.

Here part 1 is the sample and liquid cup, designed with a support disk of metal at its bottom (part 2). Part 3 is a silver sleeve introduced to reflect the light for improved volumetric readings. Part 4 is a floating ring which always stays at the water-oil-contact. This ring must be used in automatic operations with video camera and counting of pixels. The distance between the floating ring and the metal plate is then automatically detected. When the revolution is increased step by step we obtain a drainage process. The water volume will increase and the water oil contact will move towards the core inlet face (to the left in Figure 2). By decreasing the rate of revolution step by step, the positive imbibition process is obtained. Therefor we can get the capillary pressure hysteresis without changing the core cup.

RESULTS AND DISCUSSION

Ten Berea sandstone core plugs were used in the relative permeability experiments and in the primary drainage capillary pressure measurements. The reduced porosity is around 21-22% and the permeability is approximately 450 md. The rate of revolution versus time was developed separately for each range of centrifuge speeds. In addition to the Berea core plugs two chalk plugs were also included in the relative permeability study. The chalk plugs have a porosity of 40% (reduced porosity, ϕ*=0.32) and a permeability of 1 md, respectively. The chalk plugs were initially saturated with water and residual oil so secondary drainage relative permeability curves were measured. An air- brine system was used for Berea sandstone and decane-formation water was used for the chalk core plugs. Table 1 presents the fluid data and the core plug properties are summarized in Tables 2 and 3.

TABLE 1: Fluid Data at $20^{\circ}C$

Fluid	ρ (g/cm^3)	μ (10^{-3} Pas)
Brine	1.021	1.04
Air	0.001	0.0179
Formation water	1.047	1
Decane	0.764	Not measured

TABLE 2: The basic data of Berea Sandstone plugs

Core ID	D (cm)	L (cm)	k (md)	ϕ^*
D1	3.79	4.06	417	0.22
D2	3.8	4.45	425	0.21
D3	3.79	4.7	414	0.21
D4	3.8	4.34	401	0.22
D5	3.77	4.62	462	0.22
D6	3.8	4.83	485	0.22
D7	3.78	4.43	439	0.21
D8	3.81	4.47	447	0.21
D9	3.78	4.54	444	0.22
D10	3.81	4.39	407	0.22

TABLE 3: The basic data of chalk core plugs

Core ID	D (cm)	L (cm)	k (md)	ϕ*
C1	2.5	2.52	1	0.32
C2	2.5	2.36	1	0.32

Relative permeability results

The acceleration periods of the different speed intervals were recorded separately and in Figure 3 an example is shown of the relationship between the acceleration period and time for a final revolution rate of 1000 RPM

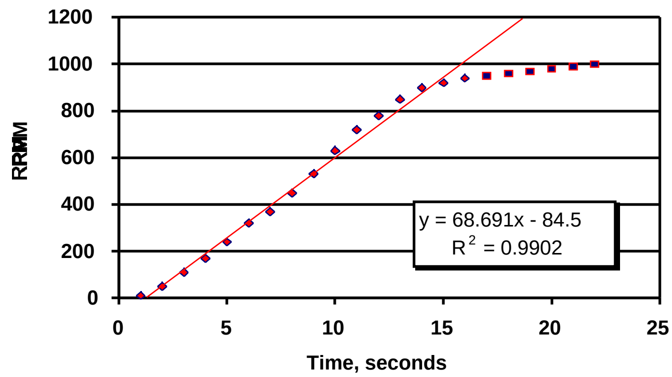

Figure 3: The acceleration period from 0 to 1000 RPM.

Relative permeability curves calculated with and without the correction due to the acceleration period were obtained for five Berea sandstone plugs. These curves are given in Figures 4 – 8. Figures 9 and 10 show relative permeabilities calculated with acceleration correction for four Berea plugs and the results indicate good reproducibility. Figures 11 and 12 present the relative permeability results of the two chalk core plugs. Due to the low permeability these core plugs are not affected by the acceleration period.

Capillary pressure results

Capillary pressure was measured on four strongly water-wet Berea sandstone core plugs and three chalk core plugs. The basic core properties are given in Table 4. The Berea sandstone core plugs were initially saturated 100% with brine. Initially the chalk core plugs were saturated with formation water and decane, and we obtained a secondary drainage process followed by a spontaneous (positive) imbibition process. The capillary pressure hysteresis curves are shown in Figures 13 – 19.

TABLE 4: The Basic data of the core plugs for capillary pressure measurements.

Core No.	L(cm)	D(cm)	Porosity (%)	Permeability (md)	Core type
6	3.21	2.48	19	500	Berea
112	3.26	2.49	20	500	Berea
A1	3.10	2.50	21	500	Berea
A2	3.12	2.50	22	500	Berea
C1	2.52	2.50	40	1	Chalk
C2	2.36	2.50	40	1	Chalk
C3	2.24	2.44	40	1	Chalk

The chalk plugs used in this study were not completely water wet due to aging in crude oil. Initially (at centrifuge speed of 0 RPM) the core plugs were saturated with initial oil saturation (S_{oi}) and the process may be represented by the secondary drainage curve, and the following imbibition process as indicated in Figure 20. As seen in Figure 20 any saturation change below the fluid/fluid interface due to imbibition will introduce an error in the calculations of the saturation changes above the fluid/fluid interface. Referring to the shaded area in the capillary pressure curve in Figure 20 the error in the average saturation ($\Delta S_{w,err}$) can be approximated by the following equation:

$$\Delta S_{w,err} = (S_{or} - S_{oi})\frac{h_f}{h_t} \quad (9)$$

Due to the local imbibition process below the fluid/fluid interface one may obtain lower oil saturation in the bottom of the core (S_{or}) than we had initially (S_{oi}). The parameters h_f and h_t are the fluid level height and the total height, respectively. As observed in Equation 9 this correction will be zero if the rock is completely water wet ($S_{oi} = S_{or}$). The error (or necessary correction) will also be small if h_f is much smaller than h_t ($h_f/h_t<0.2$). The chalk capillary pressure curves in Figures 17, 18 and 19 are not adjusted for this effect because the residual oil saturation (S_{or}) was not measured. The actual saturation may therefore be slightly higher.

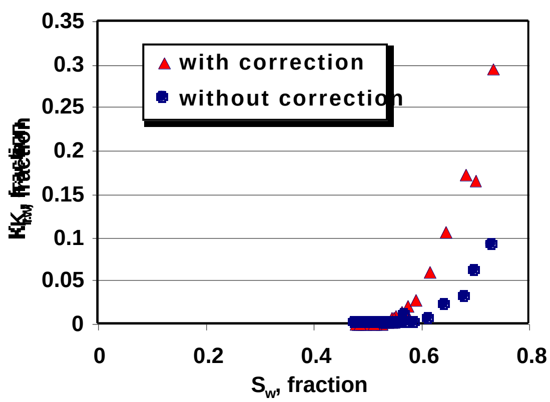

Figure 4: The water relative permeability curve of D1 from 1000RPM to 2000RPM

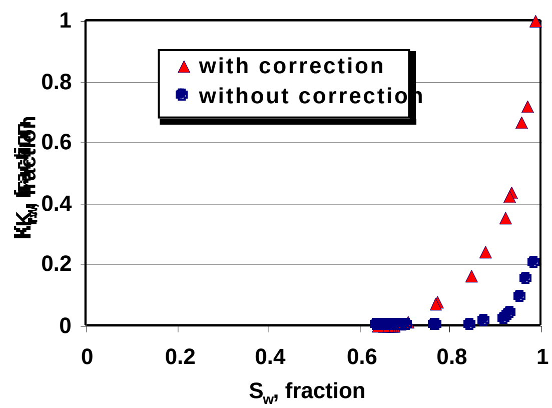

Figure 5: The water relative permeability curve of D2 from 0 to 1000RPM

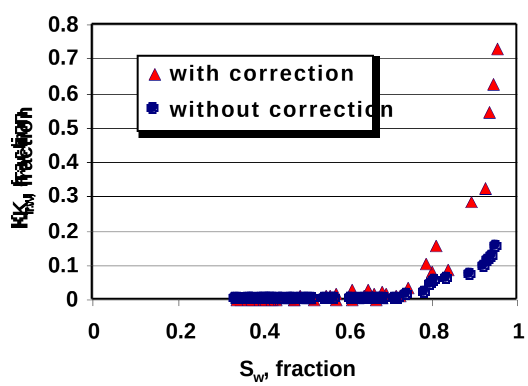

Figure 6: The water relative permeability curve of D3 from 0 to 1000RPM

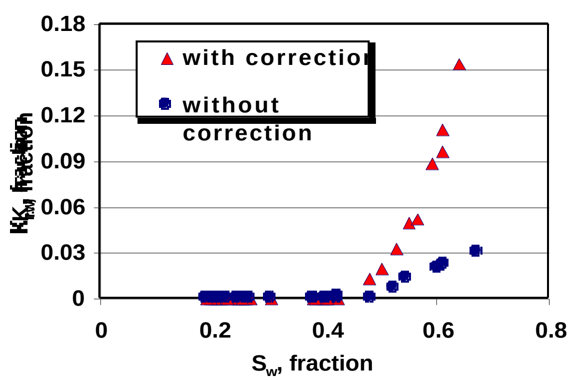

Figure 7: The water relative permeability curve of D5 from 2000RPM to 4000RPM

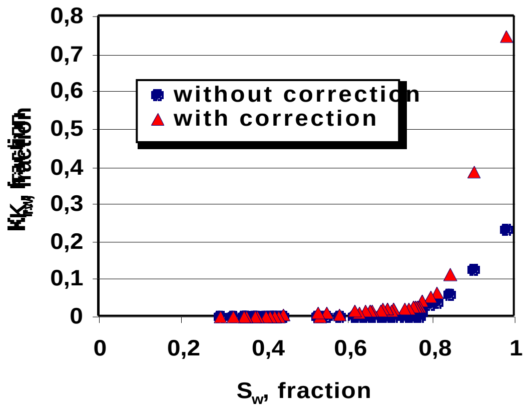

Figure 8: The water relative permeability curve of D6 from 1000RPM to 2000RPM

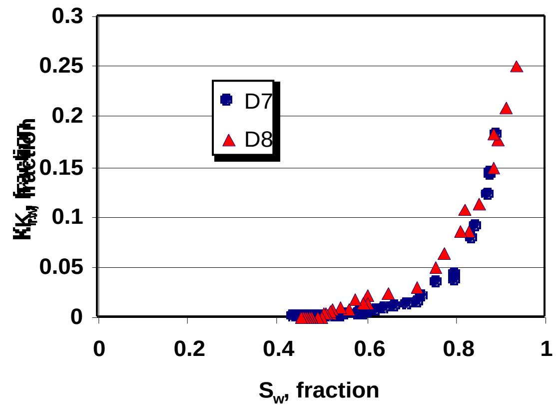

Figure 9: The water relative permeability curve of D7 and D8 from 0 to 3000RPM

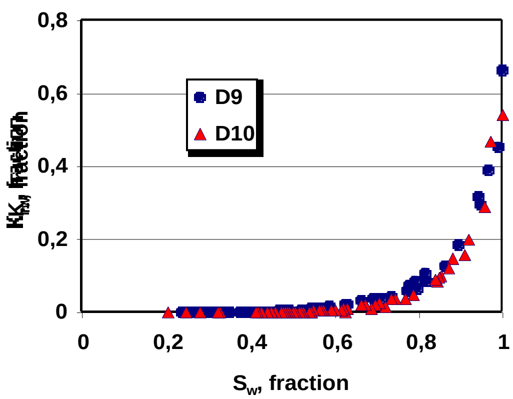

Figure 10: The water relative permeability curve of D9 and D10 from 0 to 3000RPM

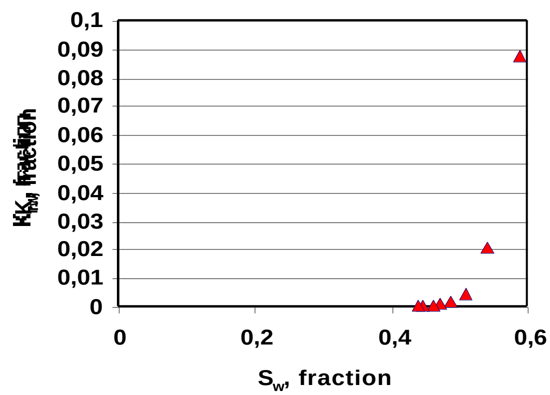

Figure 11: The water relative permeability curve of chalk C2 from 2000RPM to 4000RPM

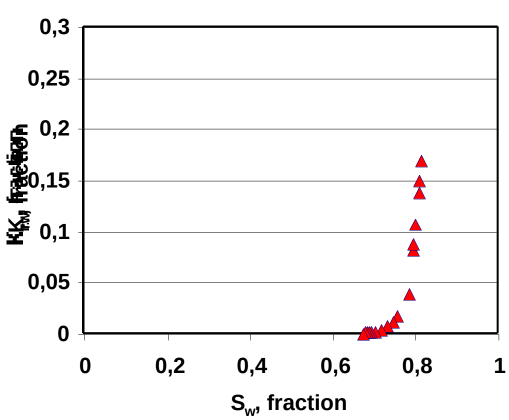

Figure 12: The water relative permeability curve of chalk C1 from 4000RPM to 6000RPM

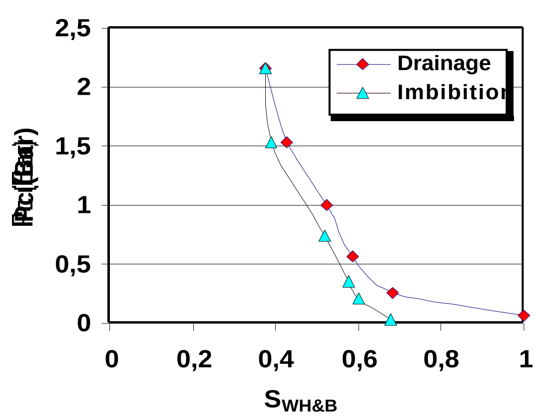

Figure 13: Capillary pressure hysteresis of Berea sandstone plug number 6

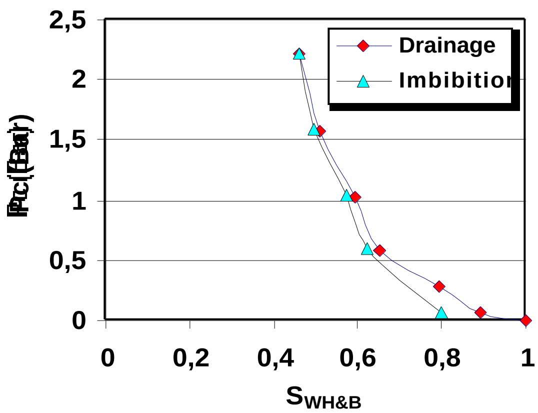

Figure 14: Capillary pressure hysteresis of Berea sandstone plug number 112

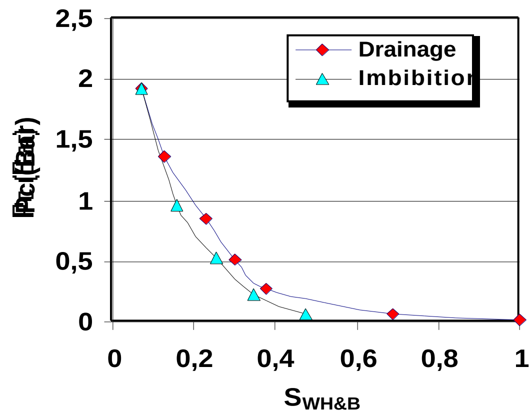

Figure 15: Capillary pressure hysteresis of Berea sandstone plug number A1

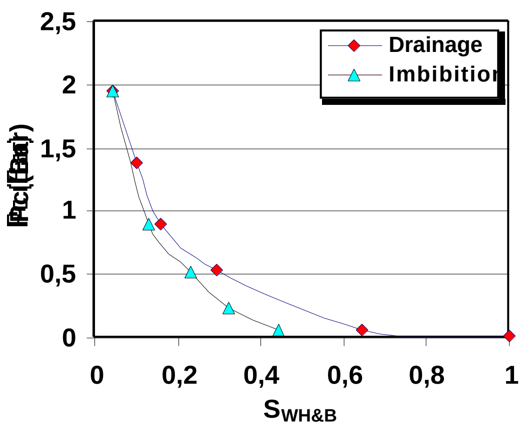

Figure 16: Capillary pressure hysteresis of Berea sandstone plug number A2

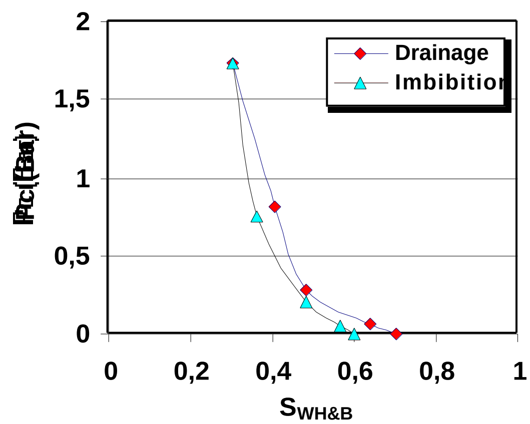

Figure 17: Capillary pressure hysteresis of chalk plug number C2

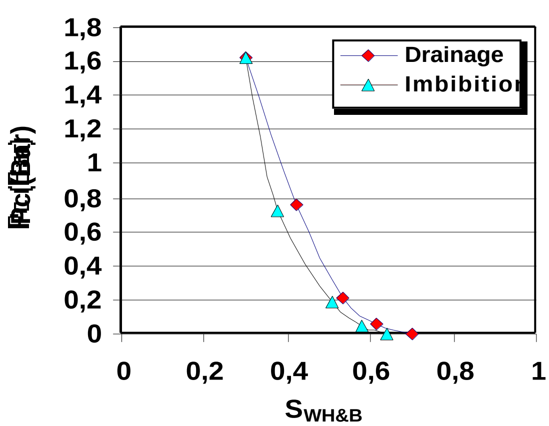

Figure 18: Capillary pressure hysteresis of chalk plug number C1

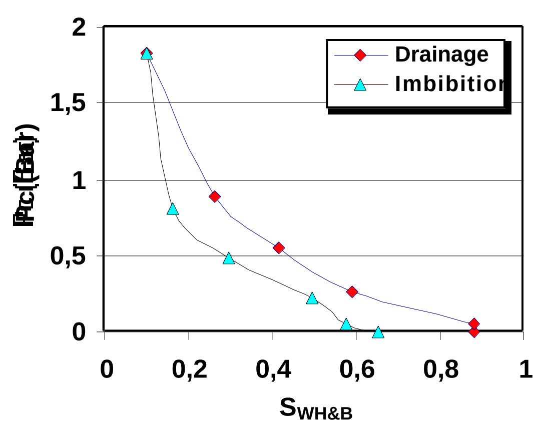

Figure 19: Capillary pressure hysteresis of chalk plug number C3

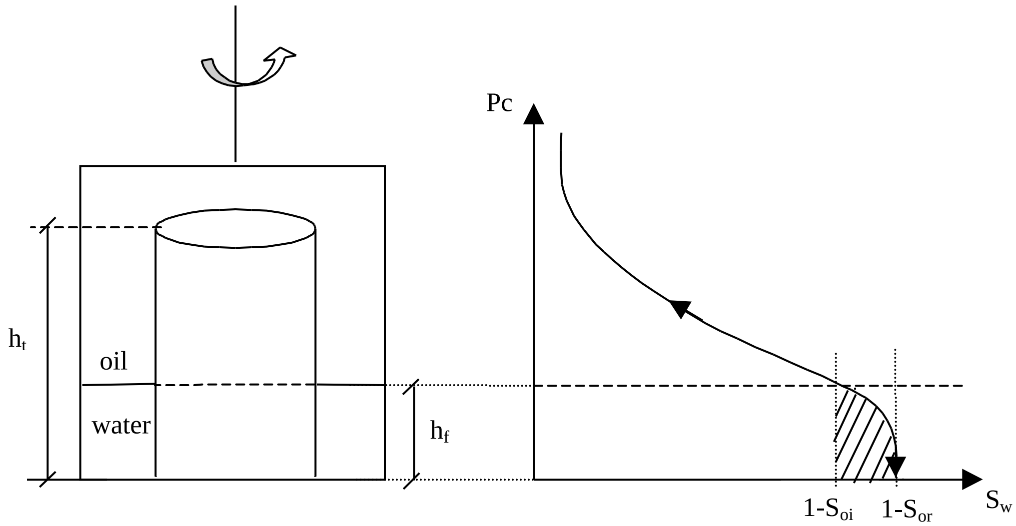

Figure 20: Schematic illustration of the capillary pressure versus saturation in the "footbath" centrifuge technique.

CONCLUSIONS

1. Analytical calculation of water/oil relative permeability curves from centrifuge experiments should include the effect of the initial acceleration period of the centrifuge. The effect of the centrifuge acceleration is significant in high permeable rocks and can be neglected in very tight rocks.

2. The moving fluid/fluid interface method for determination of drainage/imbibition capillary hysteresis is reliable for very water wet rocks, but could be erroneous for weakly water wet plugs. Only in the case of long plugs and low fluid/fluid contact level ($h_f/h_t < 0.2$) will this technique be reliable for weakly water wet plugs.

NOMENCLATURE

D	diameter
h_f	height to fluid/fluid contact
h_t	total height (core length)
k	absolute permeability
k_{rw}	water relative permeability
L	core length
N_p	cumulative water production
P_{c1}	capillary pressure ate the core inlet
r_1	distance from rotation center to core inlet
r_2	distance from rotation center to fluid/fluid contact
R_m	distance from rotation axis to core center
$S(P_{c1})$	the saturation at the core inlet
S_{oi}	initial oil saturation
S_{or}	residual oil saturation
S^*_{w2}	reduced water saturation at the core outlet
$\bar{S}(P_c)$	average water saturation of the core

t	time
t_d	dimensionless time
$\Delta S_{w,err}$	error in the average saturation
$\Delta\rho$	density difference
ϕ^*	the porosity that contains mobile fluid, $\phi^* = \phi(1-S_{or}-S_{wi})$
ρ	density
ω	angular velocity

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