UNSTEADY-STATE DISPLACEMENT COMBINED WITH CENTRIFUGE TECHNIQUE FOR MEASUREMENT OF RELATIVE PERMEABILITY

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Abstract A technique for measurement of water/oil relative permeability by using a combination of unsteady–state flooding and centrifuging is described. Both oilfloods on strongly water–wet and waterfloods on intermediate wet sandstone samples have been investigated.

The method consists of an unsteady–state flooding to obtain relative permeability of both phases and, thereafter, continuing the drainage process in a centrifuge. Compared to the flooding displacement, one will normally get a higher differential pressure across the core in a centrifuge and, thereby, achieve relative permeability values over an extended saturation range for the produced phase.

The results show for both wettability systems that the relative permeability values based on the centrifuge technique are in good agreement with those from the flooding tests, provided that the flooding displacement is correctly scaled. In the case of a strongly water–wet system an adequate scaling technique is to use the Rapoport & Leas scaling factor. However, this scaling factor is not appropriate for the intermediate wetted system. A scaling technique which simply focuses on the differential pressure across the core plug is proposed. Analysis of the results showed that by staying above a minimum value of the differential pressure, a good agreement between the flooding and the centrifuge technique was achieved.

INTRODUCTION

Two widely used techniques for measuring oil/water relative permeability are the unsteady–state and the centrifuge method. In some instances it is argued that the centrifuge method should be preferred since the unsteady–state technique normally will be influenced by capillary effects. However, there is scepticism for the use of centrifuge technique since the force applied on the core plug in a rotating centrifuge is not representative for the forces in a reservoir and consequently the results may not be reliable. In this study we wanted to combine these two methods by starting with the unsteady–state technique and then continue the drainage process in the centrifuge. In addition to giving an adequate comparison between the two methods this procedure would also produce relative permeability data over an extended saturation range compared to the unsteady–state technique alone. The advantage of finishing the drainage process in the centrifuge is related to its ability to create a high differential pressure across the core plug. Many of the interpretation techniques of an unsteady–state displacement, e.g. the Jones and Roszelle [5] technique, assume that the capillary forces are negligible. This is believed to be fulfilled at and a certain period after breakthrough provided the experiment is correctly scaled. Towards the conclusion of the displacement process, however, this assumption will be increasingly incorrect and finally there will be a balance between the capillary and the viscous forces. Techniques like that of Jones and Roszelle will interpret this as the relative permeability of the produced phase to be zero, but it might still have a certain mobility which can be proved by using a higher displacement rate or as is shown in this study by the use of centrifuging.

Two rock-fluid systems have been investigated; primary drainage process on a strongly water–wet and waterflood on an intermediate wetted system. The experiments were in both cases performed at ambient conditions.

EXPERIMENTAL PROCEDURES

Berea sandstone was used in the primary drainage experiments. The core plugs were cleaned by Dean–Stark extraction with toluene/methanol. The core material used in the waterfloods was taken from a North Sea sandstone reservoir. To avoid inhomogeneities the actual preserved sealed cores were scanned by a X-ray computer tomograph before the final selection was done. These core plugs were treated as preserved cores, ie. flushed with synthetic brine, except core plug A1 which was mildly cleaned, ie. flushed with approximately 10 pv of toluene and methanol at ambient conditions. All the experiments were conducted at ambient conditions, with a fluid system consisting of refined laboratory oil and 5% NaCl solution in the primary drainage experiments and synthetic brine in the waterfloods. Experimental, core and fluid data are shown in Table 1.

Table 1 Experimental and Core data

Core plug	Type of experiment ¶	L cm	D cm	Φ %	S_{wi}	K_{base}‡ mD	Rate ml/hour	$L\mu v$	Core material	μ_o	μ_w
DS3	W + C	6.49	3.76	21.5		334	4.92	0.12	Berea	2.48	0.92
DS1	W + C	6.37	3.76	21.8		385	50.4	1.2	Berea	2.60	0.97
DS4	W + C	6.31	3.76	21.7		361	361.0	8.62	Berea	2.52	0.94
A1	W + C	5.92	3.75	16.5 †		890	13.7	0.12	Reservoir rock 1	2.66	1.03
	W + C					842	115.8	1.06			
	W					862	361.8	3.33			
A2	W	6.47	3.74	18.0 †		1220	21.5	0.21	Reservoir rock 1	2.66	1.03
	W + C					1191	117.0	1.16			
	W + C					1109	185.4	1.88			
A3	Amott	4.70	3.73	22.8		1730			Res.rock 1		
B1	W	6.36	3.74	24.3	0.17	247	12.0	0.12	Reservoir rock 2	2.66	1.03
	W				0.17	244	24.0	0.24			
	W				0.17	246	58.0	0.60			
	W + C				0.18	231	100.0	1.04			
B2	Amott	4.85	3.75	23.6		214			Res.rock 2		
C1	W + C	6.29	3.74	23.8	0.23	115	6.0	0.06	Reservoir rock 3	2.66	1.03
	W				0.21	100	30.0	0.31			
	W + C				0.22	103	240.0	2.48			
C2	Amott	4.71	3.74	24.7		82			Res.rock 3		

† Pore volume calculated from $S_w^* = 1 - S_{wi} - S_{or}$

‡ Primary drainage: $K_{base} = K_{S_w=1}$ Waterfloods: $K_{base} = K_{o\,S_{wi}}$

¶ W: waterflood C: Centrifuging

Primary Drainage Experiments

The core plugs were oriented vertically and oil was injected at constant rate from the top. After the unsteady–state flooding the core plug was left for several days to ensure a complete redistribution of the phases. Finally the core plug was mounted in a Beckman J6B centrifuge and rotated at 3500 rpm, outer radius of 16.69 cm. As expected this lead in all cases to increased production which was interpreted by the method of Haggort [7] to give the relative permeability of the drained phase.

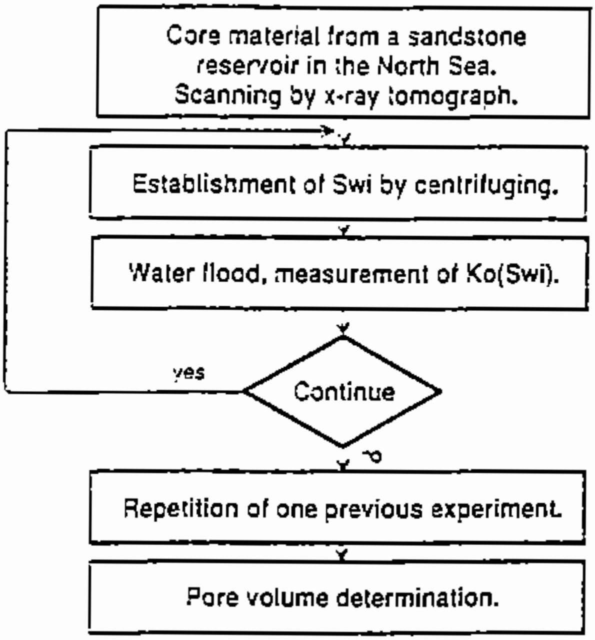

Figure 1 Scheme of experimental program on reservoir rock

Waterfloods on Intermediate Wetted Core Plugs

The reservoir core plugs were drained to S_{wi} by centrifuging in an argon atmosphere at a speed of 3000 rpm before saturating them with oil. A main purpose was to perform several unsteady–state displacements with different water injection rates on the same core and in some selected cases the drainage process was continued in a centrifuge.

This procedure would be valid if *the wettability and the $K_o(S_{wi})$ values did not change during the program.* As can be seen from Figure 1, tests of reproducibility were performed to check these assumptions. The unsteady–state experiments were performed with the cores oriented vertically and water injected from the bottom. Oil permeability at irreducible water saturation, $K_o(S_{wi})$ was measured prior to every waterflood and used as the base permeability. When the drainage process was continued in the centrifuge, the rotation speed was set to 3000 rpm, inner radius 13.15 cm.

RESULTS AND DISCUSSION

Wettability

Berea sandstone is known to be strongly water–wet and, therefore, no wettability test was carried out. However, on the preserved cores wettability tests were performed according to the Amott [4] procedure at ambient conditions. These tests were conducted on core plugs neighbouring those used in the waterfloods. The results are shown in Table 3.

Table 3 Amott wettability tests on the reservoir rock

Core plug	r_w	r_o	WI
A3	0.13	0.14	-0.01
B2	0.19	0.12	0.07
C2	0.16	0.14	0.02

The Amott tests show mixed wettability character, since both water and oil were spontaneously imbibed.

Test of Reproducibility

Two tests were performed to check reproducibility during the experimental program outlined in Figure 1. First the base permeability, $K_o(S_{wi})$, was measured before every water injection. The second reproducibility test required that an experiment performed at the begining of a test program was repeated at the end of the same program, see Figure 1. These tests have been discussed earlier by Haugen [6]. The conclusion was that neither the wettability character nor the base permeability altered significantly during the experimental program which included several waterfloods on the same core.

Relative Permeability to Water from Primary Drainage Oilflood combined with Centrifuge Drainage

Figure 2 summarizes the relative permeability curves, k_{rw}, from three tests combining unsteady–state and the centrifuge technique. Three main observations can be made from this figure. The data for k_{rw} from all three centrifuge experiments fall nearly in the same curve, the data for k_{rw} from the unsteady–state experiment DS04, which according to the Rapoport and Leas criterion [1], $L\mu v > 1 - 5$, was correctly scaled, coincide very well with the centrifuge data. While a considerable discrepancy is observed between the unsteady–state and the centrifuge data in case of experiments DS03 and DS01, none of them correctly scaled. The discrepancy is found to increase with decreasing value of the scaling factor $L\mu v$. Finally, a close look reveals that the first centrifuge data point follows the last unsteady–state data by only a few saturation percent. It should also be noted that the first centrifuge data fell upon the assumed correct k_{rw} curve immediately, there is no sign of any hysteresis effect.

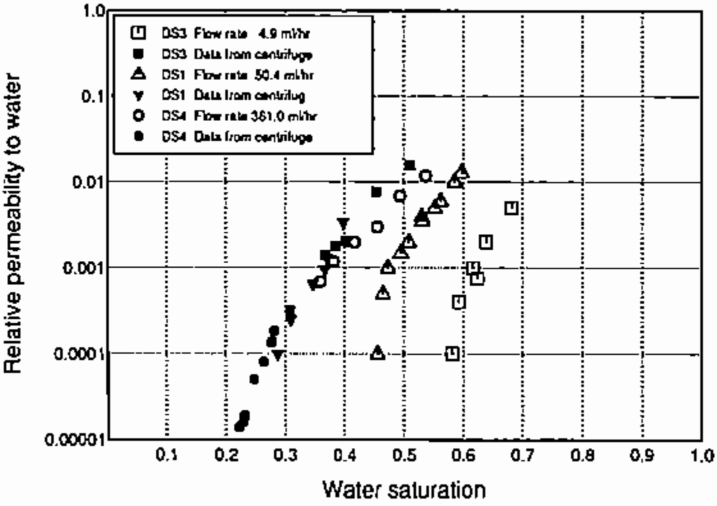

Figure 2 Primary drainage on Berea Sandstone.

Relative Permeability to Oil from Waterfloods combined with Centrifuge Drainage

Figure 3 to 6 summarize the k_{ro} results from tests on the four reservoir core plugs. Core plug C1 had the lowest permeability, 107 mD in average. An excellent agreement with respect to k_{ro} is found between the two centrifuge experiments and also between these and the k_{ro} data from the unsteady-state experiment with injection rate 240.0 ml/hour. The intermediate injection rate, 30 ml/hour, produced k_{ro} data that was not or only to a minor degree affected by capillary effects. An injection rate of 6 ml/hour, however, gave k_{ro} data influenced by capillary effects especially at the end as could be expected.

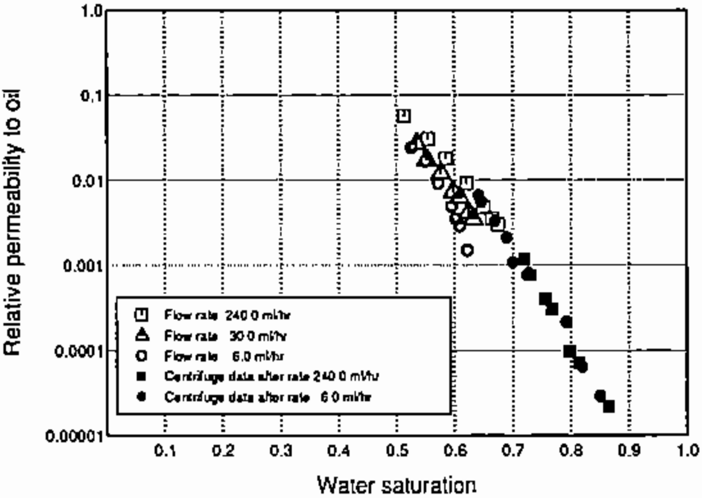

Figure 3 Results on core plug C1, average permeability of 107 mD.

The next core plug, B1, had an average permeability of 244 mD. The result from the centrifuge experiment is in excellent agreement with the combined waterflood experiment with an injection rate of 100 ml/hour. An injection rate of 58.0 ml/hour probably gave correct data while the two waterflood experiments with the lowest injection rates are observed to be influenced by capillary effects.

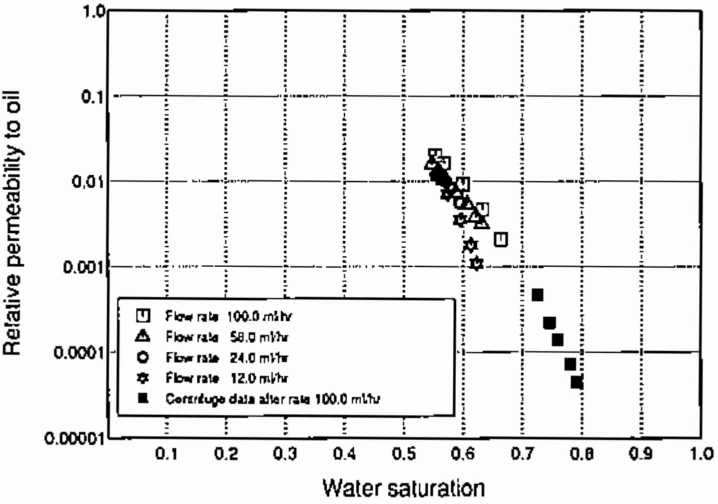

Figure 4 Results on core plug B1, average permeability of 244 mD.

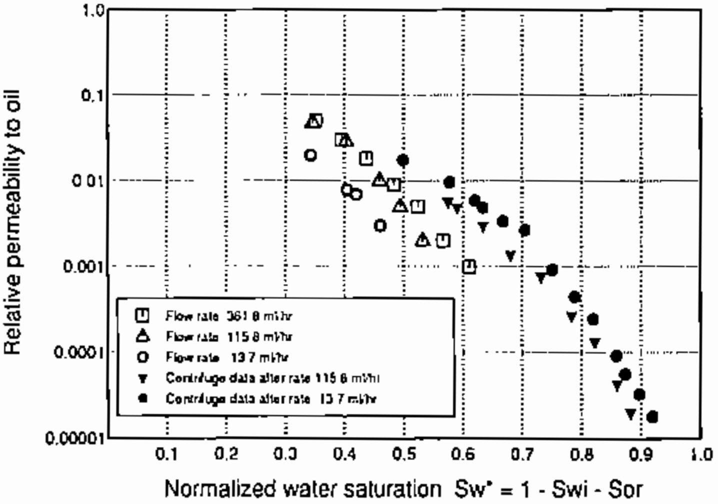

Figure 5 Results on core plug A1, average permeability of 870 mD.

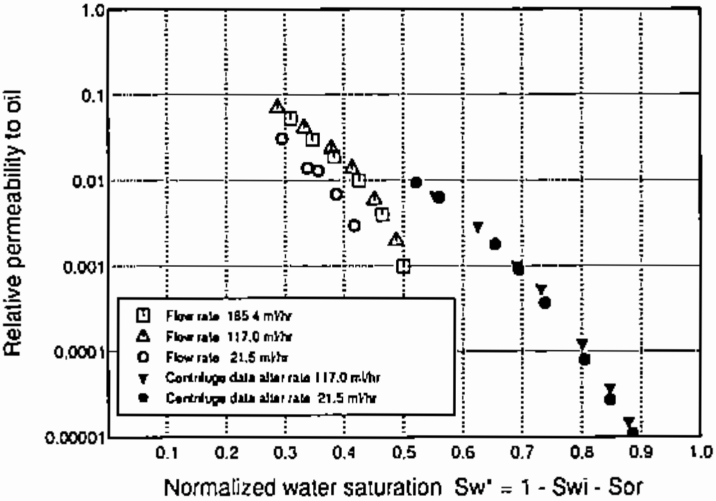

Figure 6 Results on core plug A2, average permeability of 1148 mD.

Two combined experiments were performed on core plug A1 and now a clear discrepancy is observed between the two techniques. The first k_{ro} data from the centrifuge technique are significantly higher compared to those obtained at the conclusion of the waterfloods. Even the high–rate experiment at 361.8 ml/hour cannot match the centrifuge data. The agreement between the two sets of centrifuge data remains good.

This discrepancy is even more noticeable in the case of core plug A2, the one with the highest average permeability of 1148 mD. All the waterflood experiments seem to be influenced by capillary effects, i.e., not to be correctly scaled. The centrifuge data do again show excellent agreement.

Interpretation

In the case of the primary drainage experiments a good agreement was found between the unsteady–state and centrifuge techniques, provided that the unsteady–state experiment was correctly scaled and the scaling criterion to Rapoport and Leas, $L\mu v > 1 - 5$, proved to be adequate in this respect. When it comes to waterfloods on intermediate wetted core material, the observed discrepancy is found to be a function of absolute permeability and

Table 4

Core	$K_o(S_{wi})$ mD	Rate ml/hour	ΔP_{end} kPa	Correct k_{ro}? †
C1	115	6.0	4.8	no
	100	30.0	15.9	yes?
	103	240.0	94.5	yes
B1	247	12.0	4.1	no
	244	24.0	11.0	no
	246	58.0	15.9	yes?
	231	100.0	24.1	yes
A1	890	13.7	1.4	no
	842	115.8	5.5	no
	862	361.5	12.4	no
A2	1220	21.5	2.1	no
	1191	117.0	4.1	no
	1109	185.4	5.5	no

† Judged by visual control of Figures 3 to 6

therefore the scaling criterion $L\mu v > 1 - 5$ will not be useful. Instead the observations suggest rather that focus should be put on differential pressure across the core plug since there is proportionality between this parameter and absolute permeability. In Table 4 the differential pressure across the core plugs at the conclusion of the waterfloods are given. Column 5 indicates whether the experiment was regarded to give correct, k_{ro}, or in other words, if the experiment was correctly scaled. This judgment is based on visual consideration of Figures 3 to 6, see discussion above.

An experiment will then, according to this approach, be correctly scaled when $\Delta P_{end} > 17 - 21\ kPa$. This can be achieved by using a sufficiently highly injection rate which for highly permeable cores may be so high that it is not desirable for other reasons, e.g., the danger of an unstable displacement Haugen [6], Peters [3] or a non–representative flow regime, Heaviside et al [2]. This means that, in such a case and for a given rock/fluid system, the only way to scale the experiment correctly will be to increase the core length.

It should be stressed that these conclusions are primarily relevant when using interpretation methods that are based on the assumption of negligible capillary effects like the Jones and Roszelle technique.

CONCLUSIONS

1. It is demonstrated that by applying the centrifuge technique after an unsteady state displacement it is possible to obtain relative permeability data for the drained phase over an extended saturation range.
2. There is excellent agreement between the the unsteady–state and the centrifuge relative permeability data provided that the unsteady–state experiment is correctly scaled.
3. In the case of a drainage process on a strongly wetted system, the scaling criterion, $L\mu v > 1 - 5$, suggested by Rapoport and Leas proved to be adequate.
4. On intermediate wetted core material, a scaling criterion is proposed which states that the differential pressure across the core at the conclusion of an unsteady–state displacement should be higher than a critical value. This critical value may depend on the wettability, but was found to be in the order of 17–21 kPa for the reservoir rock in this study, which according to the Amott wettability test showed typically mixed wet character.

NOMENCLATURE

D	core plug diameter
$K_{S_w=1}$	water permeability on cleaned core
K_{base}	base permeability
$K_o(S_{wi})$	oil permeability at irreducible water saturation
k_{rw}	relative permeability to water
k_{ro}	relative permeability to oil
L	core plug length
$L\mu v$	scaling factor
ΔP_{end}	differential pressure across the core at the conclusion of the waterflood
PV	pore volume

r_o	$\dfrac{\text{oil displaced by water imbibition}}{\text{oil displaced by (water imbibition + centrifuging)}}$
r_w	$\dfrac{\text{water displaced by oil imbibition}}{\text{water displaced by (oil imbibition + centrifuging)}}$
S_w^*	normalized water saturation
S_{or}	residual oil saturation
S_{wi}	irreducible water saturation
WI	Amott wettability index
Φ	porosity
μ	viscosity

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