SCALING CRITERION FOR RELATIVE PERMEABILITY EXPERIMENTS ON SAMPLES WITH INTERMEDIATE WETTABILITY

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Abstract Measurement of relative permeability by the unsteady–state technique poses problems when dealing with rocks of intermediate wettability. Scaling criteria established for cores with strongly wetted rock require flooding rates much higher than a realistic reservoir rate and may cause an unstable displacement or a non–representative flow regime. This paper presents results from waterfloods on reservoir sandstone cores of intermediate wettability. The tests presented were conducted at ambient conditions using synthetic brine and laboratory oil. The flooding rate was varied in steps from low to high, and the absolute permeability varied from 107 mD to 870 mD. The results show that the type of scaling criteria applied to strongly water–wet cores probably also holds for intermediate wettability systems but with different critical values. This means that correctly scaled experiments can be performed on intermediate wettability systems at lower rates than for strongly wetted systems. The high rate tests were, according to the stability criteria used, influenced by viscous fingering, and should therefore not be used for calculation of relative permeability.

INTRODUCTION

Unsteady-state water/oil relative permeability experiments are often carefully designed to reproduce the in-situ reservoir conditions as closely as possible. Realistic wettability, reservoir fluids, pressure and temperature are often applied. However the flow rates are normally higher than typical reservoirs rates in order to overcome capillary effects. There are three capillary effects related to laboratory experiments; dispersion of the front, end effects and when capillary forces dominate the viscous forces on a microscopic scale. Rapoport and Leas [1] developed a scaling criterion in order to overcome the capillary effect during a water/oil displacement in a strongly wetted system. However, it has been claimed that these scaling criteria are not valid when dealing with intermediately wetted reservoirs. According to Heaviside et al. [2], there exists a fine balance between viscous and capillary forces in a reservoir. This balance will not be maintained in an experiment if the flow rate is higher than the reservoir rate. This results in a non–representative flow regime and the subsequent relative permeability calculations will also be incorrect. High flow rates may also cause unstable displacement, i.e. viscous fingering. Peters [3] has developed a criterion that must be met in order to achieve stable displacement, and has also showed the effect on the relative permeability curves when unstable displacement occurs [4].

The aim of this study is to investigate the effect of rate on relative permeability curves:

i) On intermediately wetted cores, i.e. weak, mixed or neutrally wetted cores
ii) Over a wide rate and permeability range
iii) To perform the experiments under well-controlled conditions.
iv) From these investigations recommend scaling criteria for future experiments.

THEORY

Based on the applicability of Darcy's law, a one–dimensional immiscible and incompressible oil/water flow in a porous medium is described by the following equation [1]:

$$\frac{\partial S}{\partial T} + \frac{dF}{dS}\frac{\partial S}{\partial X} - \frac{1}{L\mu_w v}\frac{\partial}{\partial X}\left(K_o F \frac{dP_c}{dS}\frac{\partial S}{\partial X}\right) = 0 \qquad (1)$$

All the symbols used are defined in the appended nomenclature list. Capillary forces are represented in the third term, containing "the scaling coefficient", $L\mu_w v$, as described by Rapoport and Leas. They maintained that the capillary forces could be neglected if the value of this scaling coefficient was sufficiently high. This specific value can not be predicted theoretically, but must be experimentally measured. If capillary forces can be omitted from equation (1), the flow is said to be stabilized, which means that shape of the front does not change with time. It should be pointed out that equation (1) represents the two-phase flow inside a porous medium, *it does not take into account what is happening on the inlet or outlet face, the so–called end effects.*

Peters [3] studied stability during two-phase flow and has derived a dimensionless parameter, called the stability number, which may be used to define the boundary between stable and unstable displacement. For a cylindrical system, the onset of instability is defined by:

$$\frac{(M_r - 1)(v - v_c)\mu_w D^2}{C\gamma K_{wr}} = 13.56 \qquad (2)$$

The wettability parameter C must be determined experimentally; Peters estimated C to be 306 for a water–wet system and 5.5 for an oil–wet system.

A simplified version of equation (2) was suggested by Demetre et al [5]:

$$\frac{(\mu_o/\mu_w - 1)\, v\mu_w D^2}{C\gamma K} = 13.56 \qquad (3)$$

Equation (3) is used in this study.

EXPERIMENTAL PROCEDURES

The core material used in this study was taken from a North Sea sandstone reservoir. Basic data are given in Table 1. To avoid inhomogeneities the actual preserved sealed cores were scanned by a X-ray computer tomograph before the final selection was done. All the cores, with the exception of core plug A1, were treated as preserved cores, i.e. flushed with synthetic brine.

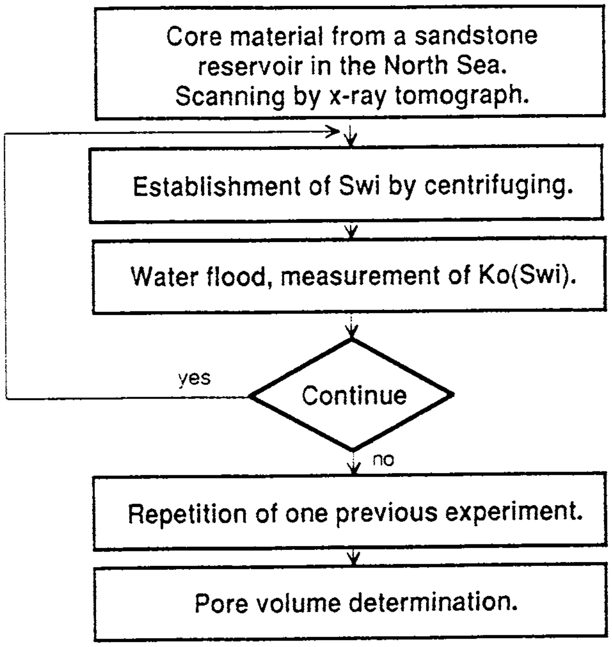

Figure 1 Scheme of experimental program.

Table 1 Core data

Core Plug	Type of experiment	Length cm	Diameter cm	Porosity %	$K_o(S_{wi})$ mD	Remarks
A1	Waterflood	5.92	3.75	16.5 †	870	From the same seal peal
A2	Waterflood	6.47	3.74	18.0 †	1160	
A3	Amott test	4.70	3.73	22.8	1730	
B1	Waterflood	6.36	3.74	24.3	244	From the same seal peal
B2	Amott test	4.85	3.75	23.6	214	
C1	Waterflood	6.29	3.74	23.8	107	From the same seal peal
C2	Amott test	4.71	3.74	24.7	82	

†Pore volume based on $S_w^* = 1 - S_{wi} - S_{or}$

Core plug A1 was cleaned mildly, i.e. flushed with approximately 10 PV of toluene and methanol at ambient conditions. The core plugs were then drained to S_{wi} in an argon atmosphere using a centrifuge rotating at 3000 rpm. All the experiments were conducted at ambient conditions, with a fluid system consisting of synthetic brine and refined laboratory oil. Viscosity data are given in Table 2.

A main idea was to perform several unsteady-state displacements with different water injection rates on the same core. Figure 1 outlines the experimental program. This procedure will be valid if *the wettability and the* $K_o(S_{wi})$ *values do 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. Oil permeability at irreducible water saturation, $K_o(S_{wi})$ was measured prior to every water injection and used as the base permeability.

Table 2 Fluid viscosity data

Fluid	Viscosity † $mPas$
Brine	1.03
Refined lab. oil	2.66

†*Measured at* 23 *C*

RESULTS AND DISCUSSION

Wettability

Wettability tests were performed according to the Amott procedure [6] at ambient conditions on preserved cores. These tests were conducted on neighbouring core plugs to the ones used in the waterfloods. The results are shown in Table 3 (see also Table 1). The Amott tests show mixed wettability character, since both water and oil spontaneously imbibed, and thus meet one important requirement.

Table 3 Amott wettability tests

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

Test of Reproducibility

Two tests were performed to check reproducibility. First the base permeability, $K_o(S_{wi})$, was measured before every water injection (Table 1). The average values calculated together with the standard deviation are shown in Table 4. The variation in base permeability is found to be small and unsystematic.

Table 4 Average base permeabilities

Core	$K_o(S_{wi})$	Standard deviation	
Plug	mD	%	mD
A1	870	2.6	22
A2	1160	4.3	50
B1	244	2.5	6
C1	107	6.5	7

The second reproducibility test required that an experiment performed at the beginning of a test program was repeated at the end of the same program, see Figure 1. Table 5 shows when these repeated experiments were performed. Figure 2 presents the resulting relative permeability curves. With the exception of the k_{rw} values for core plug B1, the reproducibility is very good.

The conclusion from these tests is that neither the wettability character nor the base permeability altered significantly during the experimental program which included several waterfloods on the same core. The goal of performing the experiments under well-controlled conditions is therefore fulfilled.

Relative Permeability to Oil

The main experimental data is given in Table 5. Relative permeability to oil calculated using the Jones and Roszelle technique [7] are presented in Figure 3. The relative permeability results for core plug A2 were nearly identical

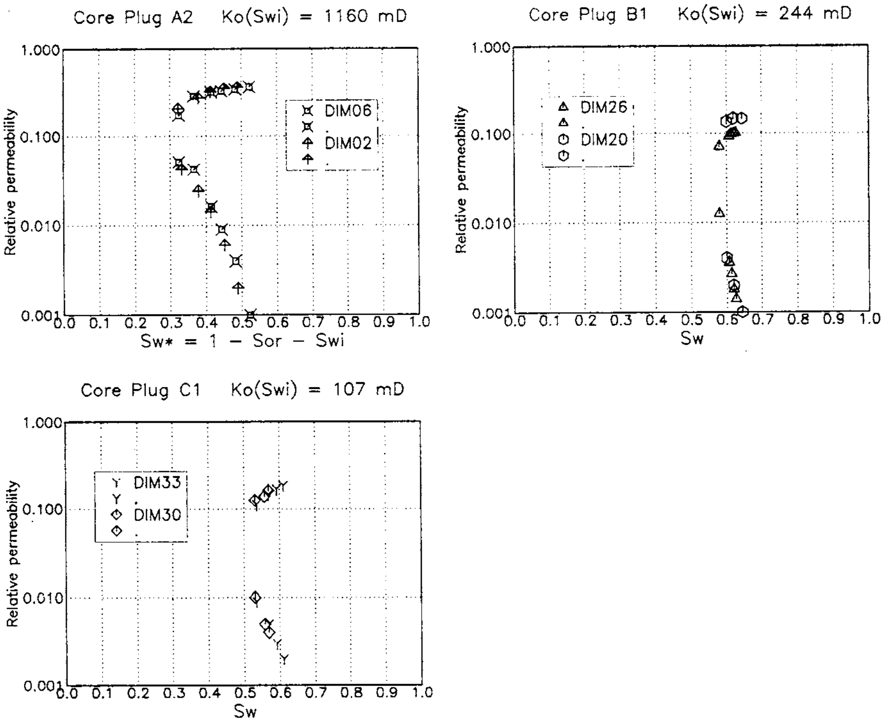

Figure 2 Repeated relative permeability measurements

with the results for the neighbouring core plug A1 and are therefore not reported. It should be noted that core plug A1 was damaged immediately before the pore volume determination (Figure 1). This is why the saturation range in this case is normalized to $S_w^* = 1 - S_{wi} - S_{orw}$. The S_{orw} value was determined by centrifuging.

With the exception of the low rate experiment on core plug A1 (a rate of 13.7 cc/hour), there is a very good consistency in the results. The main observations are: (i) Different flow rates give the same k_{ro} values immediately after breakthrough and over a certain saturation range; (ii) At the end of the displacement process there is a systematic relationship between decreasing k_{ro} values and decreasing flow rate. This behaviour is, however, not necessarily a capillary end–effect, but may also be a general capillary effect that occurs at the conclusion of the displacements. From this we may conclude that no rate effect is found for the first part of the k_{ro} curves but at the end a systematic rate effect is observed.

Table 5 Experimental data

Core Plug	Experiment	S_{wi}	$K_o(S_{wi})$ mD	Injection Rate cc/hour	Recovery		$L\mu_w v$ cm^2cP/min	N_s
					at BT %	total %		
A2	DIM02		1191	117.0	27	52	1.16	8.5
	DIM03		1220	21.5	27	43	0.21	1.5
	DIM06		1134	113.4	28	52	1.15	8.8
	DIM08		1109	185.4	26	51	1.88	14.6
A1	DIM01		842	115.8	27	51	1.06	12.1
	DIM04		890	13.7	27	42	0.12	1.3
	DIM05		862	361.8	23	56	3.33	36.1
	DIM07		888	277.5	23	56	2.53	27.2
B1	DIM20	0.16	246	6.0	39	46	0.06	2.2
	DIM21	0.17	247	12.0	39	48	0.12	4.2
	DIM22	0.17	244	24.0	40	51	0.24	6.7
	DIM23	0.17	246	58.0	39	51	0.60	21.4
	DIM24	0.18	231	100.0	37	52	1.04	39.8
	DIM25	0.21	247	300.0	35	54	3.1	105.8
	DIM26	0.18	248	6.0	40	48	0.06	2.0
C1	DIM30	0.23	115	6.0	33	43	0.06	4.5
	DIM31	0.21	100	30.0	32	47	0.31	27.4
	DIM32	0.22	103	240.0	31	50	2.48	202.9
	DIM33	0.21	111	6.0	33	43	0.06	4.7

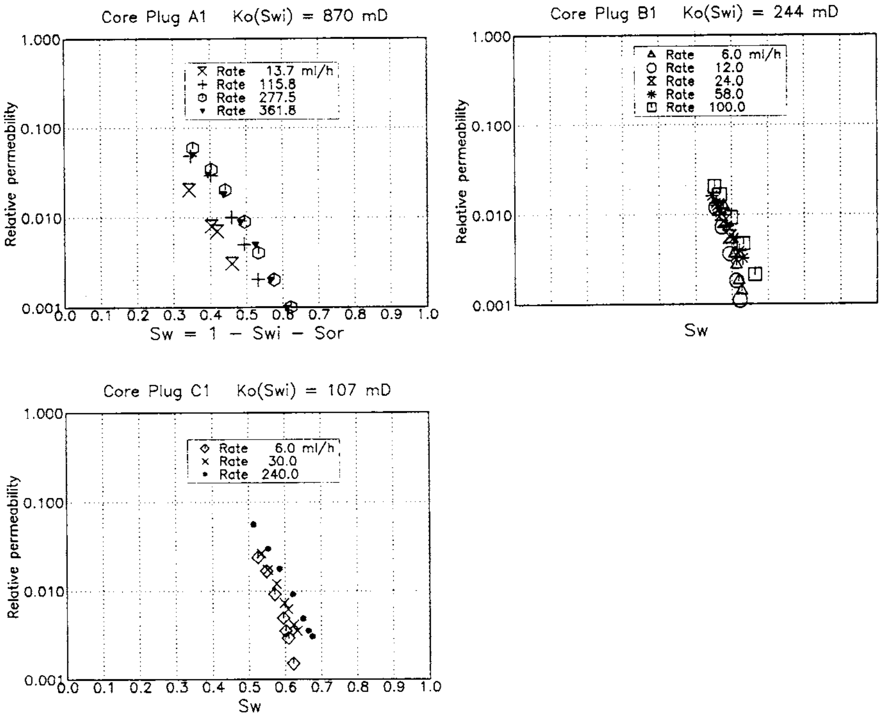

Figure 3 Relative permeability to oil

In the case of the low rate experiment on core plug A1, however, a significant effect is observed. This experiment will be further discussed later in the text.

Scaling Coefficient $L\mu_w v$

Rapoport et al. [1] theoretically derived a scaling coefficient $L\mu_w v$ and found experimentally that $L\mu_w v > 1 - 5$ would establish a stabilized flow; i.e. flow in which the shape of the front does not change during time. Stabilized flow was achieved when recovery at breakthrough reached a maximum. Figure 4 shows the relationship between $L\mu_w v$ and recovery at breakthrough for three core plugs in this study. It can be seen that even at the lowest flow rates maximum recovery at breakthrough is achieved. The criterion of $L\mu_w v > 1-5$, empirically determined on strongly wetted systems, is clearly too strong when it comes to intermediately wetted systems. This is due to the fact that on strongly wetted core material, the front will need more energy or time

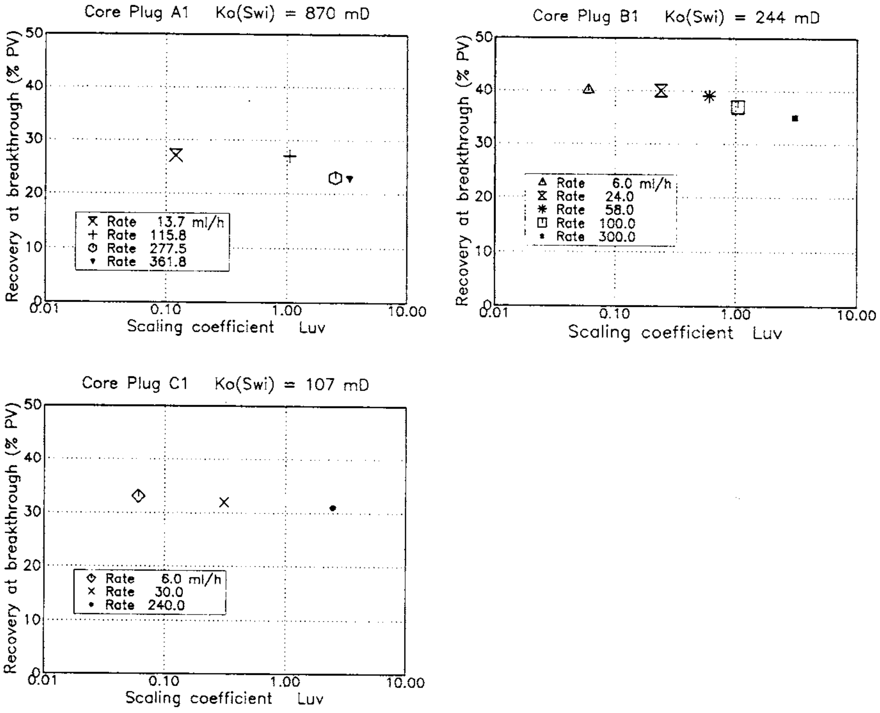

Figure 4 Scaling coefficient $L\mu_w v$ versus recovery at Breakthrough.

to be stabilized as compared to cores with weaker capillary forces. This is even more likely in this particular case with mixed wettability, since both an imbibition and drainage process will take place. The main conclusion for this particular wetted system is that a scaling coefficient of $L\mu_w v > 0.10$ is sufficient to achieve a stabilized flow. The other interesting observation from Figure 4 is the fact that recovery begins to decrease when $L\mu_w v$ becomes larger than about 1.0. This is an indication of fingering and is the subject of the next chapter.

Unstable Displacement

In Figure 4 a significant decrease in recovery at breakthrough was observed for high flow rates for core plugs A1 and B1; in the case of core plug C1, the effect was small, if any. This decrease in recovery at breakthrough is believed to be caused by viscous fingering. Equation (3) was used to check for stabil-

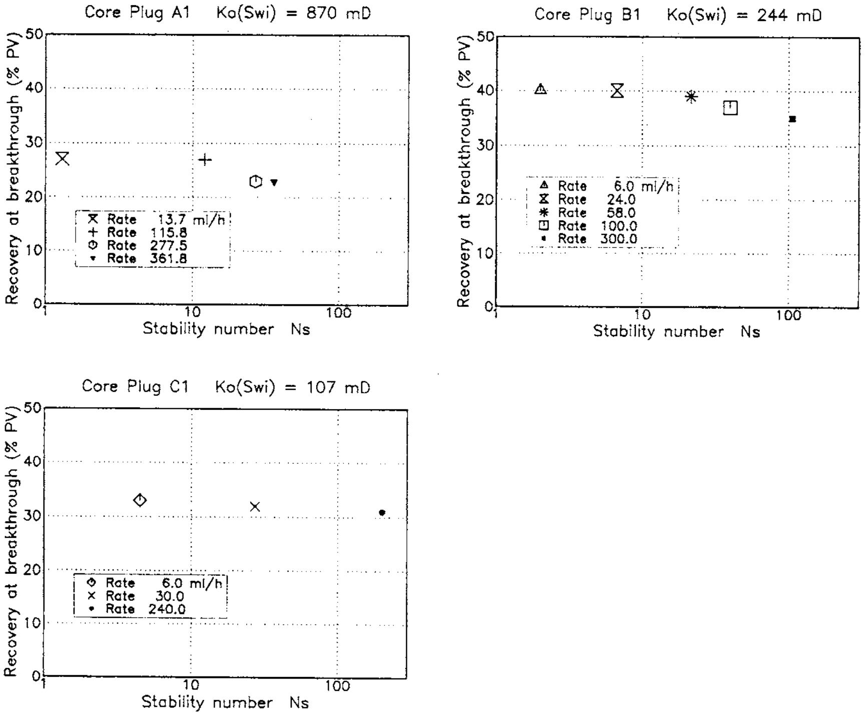

Figure 5 Stability Number, N_s, versus recovery at breakthrough.

ity, with the wettability parameter C as the only unknown parameter. By trial and error, C was determined so that recovery at breakthrough started to decline at $N_s = 13.5$, and was found to be 150 for all three core plugs. The parameter N_s could then be calculated, see Table 5, and plotted against recovery at breakthrough as given in Figure 5. Two important observations should be made: (i) The value of C that led to unstable displacement at the critical value, $N_s = 13.5$, was found to be equal for three different permeabilities. This is as expected since C is a wettability parameter and the core plugs have similar wettability as shown earlier; (ii) For this particular wetting system, C was found to be 150, which lies midway between strongly water–wet ($C = 305$) and strongly oil–wet ($C = 5.5$) systems, indicating intermediately wetted rock. This is in agreement with the Amott wettability tests.

Our results seem to be in good agreement with Peter's stability theory. The conclusion from this must be that this type of stability criterion has proved to be useful to define the boundary between stable and unstable displacement.

Relative Permeability to Water

Figure 6 shows the calculated k_{rw} values for the three core plugs with various flow rates on a linear scale. In the case of core plug C1, the rate dependency is rather low, although some effects are seen. The experiments run at flow rates of 30.0 and 240.0 cc/hour give very similar k_{rw} curves and they lie above the curve from the low rate experiment. From Figure 5 it can be seen that the two high–rate experiments probably resulted in unstable displacements. The conclusion is that the low–rate experiment, with a flow rate of 6.0 cc/hour, gives the most correct data.

For core plug B1, we see the same trend as for core plug C1. The two experiments with the highest rates, 100.0 and 300.0 cc/hour, are found to give unstable displacements and are therefore rejected. The low rate experiment, at 6.0 cc/hour, gives a significantly lower k_{rw} value than the others. Referring to Figure 4, it is found that in spite of a very low scaling coefficient, $L\mu_w v = 0.06$, the front was stabilized. However, it is believed that the flow was influenced by capillary forces almost immediately after breakthrough, owing to the very low differential pressure across the core. The remaining two k_{rw} curves, based on the experiments with flow rates of 12.0 and 24.0 cc/hour, are believed to be the most reliable.

Finally, core plug A1, showed a strong rate dependency of k_{rw}. Again, the two experiments with the highest flow rates, 277.5 and 361.8 cc/hour, were found to be unstable and are therefore rejected. The low rate experiment is considered to be affected by capillary forces, this is also verified by the k_{ro} curve from this experiment (Figure 3), thus the interpretation technique of Jones and Roszelle is not valid. This leaves the result from the experiment with a flow rate of 115.8 cc/hour. Based on the fact that the front proved to be stabilized at the time of breakthrough, that the displacement is considered to be stable and that the k_{ro} data seem to be correct, it can be deduced that k_{rw} data from this experiment are the most correct. However, with absolute permeability of this order, 870 mD, it is advisable to extend the core plug length in such experiments.

As showing above, it is seen that $L\mu_w v > 0.10$ was sufficient to achieve a stabilized front at breakthrough, for mixed wettability systems. The results in this chapter show, however, that the flow might be influenced by capillary forces almost immediately after breakthrough. Therefore, $L\mu_w v > 0.10$ is not considered to be a sufficient criterion for scaling experiments on cores with high permeability. To obtain a flow that is not severely influenced by capillary forces after breakthrough, it is necessary to have a certain minimum differential pressure across the core. To secure a sufficient differential pres-

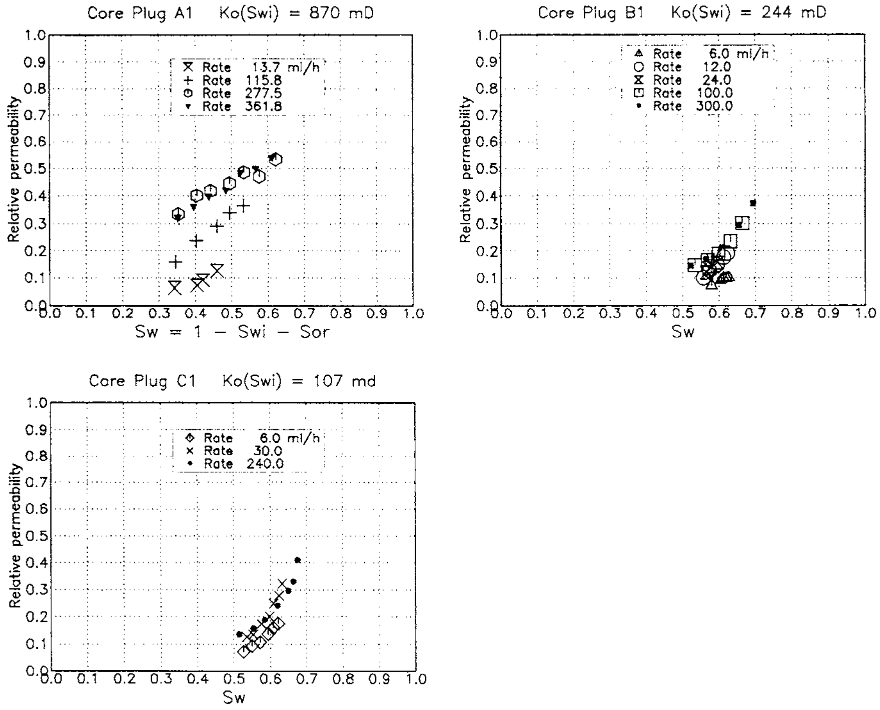

Figure 6 Relative permeability to water

sure across the core, but not so high that unstable displacement takes place, is believed to be a useful guideline in these kind of experiments. Among the above experiments that were considered to be reliable, it was found that the differential pressure during the oil flow previous to the water flood (the same flow rate is used) was in all cases between 2.7 and 6.8 kPa. It must be emphasized, however, that the value of this differential pressure is dependent both on wettability and fluid characteristics, especially fluid viscosities.

CONCLUSIONS

A number of dynamic waterflood displacement experiments were conducted on the same core plug under well controlled conditions, and lead to the following conclusions:

1. Relative permeability to oil showed little rate dependency in the first part of the k_{ro} curve. A rate effect was seen at the end of the displacement causing underestimation of relative permeability to oil at low oil saturations.
2. The stability number, N_s, was successfully used to distinguish between stable and unstable displacement. The wettability parameter C in N_s was found to be 150.
3. Values of the scaling coefficient $L\mu_w v > 0.10$ proved to be sufficient to achieve a stabilized front at the time of breakthrough.
4. However, this scaling criterion was not sufficient in some of the experiments to avoid a capillary effect just after breakthrough. This was found to be a problem with high permeability samples. The best way to compensate for this is to extend the core plug length.
5. On core material of intermediate wettability, waterfloods should be conducted at rates that create a sufficiently high differential pressure across the core plug to secure a stabilized flow at breakthrough and a flow after breakthrough that is not affected by capillary effects. However, the rate must be sufficiently low to avoid unstable displacement. A suitable pressure gradient in this study was found to be between 2.7 and 6.8 kPa, but this will depend upon wettability and fluid viscosities.

NOMENCLATURE

Latin

BT	breakthrough
C	dimensionless wettability parameter
F	fractional flow
$K_w(S_w = 1)$	water permeability on cleaned core
K_{wr}	effective water permeability at S_{orw}
K	absolute liquid 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
M_r	mobility ratio
N_s	stability number

P_c	capillary pressure
PV	pore volume
r_o	$\frac{\text{oil displaced by water imbibition}}{\text{oil displaced by (water imbibition + centrifuging)}}$
r_w	$\frac{\text{water displaced by oil imbibition}}{\text{water displaced by (oil imbibition + centrifuging)}}$
S_w, S	water saturation
S_w^*	normalized water saturation
S_{orw}	residual oil saturation
S_{wi}	irreducible water saturation
T	dimensionless time coordinator
v	Darcy rate
v_c	critical rate that always ensure stable displacement
WI	Amott wettability index
X	dimensionless space coordinator

Greek

Φ	porosity
μ	viscosity
γ	interfacial tension

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