INITIAL WATER SATURATION AND OIL RECOVERY FROM CHALK AND SANDSTONE BY SPONTANEOUS IMBIBITION

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ABSTRACT

Spontaneous imbibition is of special importance to the efficiency of oil recovery from fractured reservoirs. Many factors affect the process of spontaneous imbibition. This paper presents an investigation of the effect of rock properties and initial water saturation, S_{wi}.

In all, 59 imbibition curves are presented for various types of chalk and sandstone. Final recovery for Berea sandstone expressed as percent of original oil in place (OOIP) showed only a few percent variation with change in initial water saturation. Final recovery for chalk showed much greater variation; for two of the chalk sample sets, oil recovery decreased systematically with increase in S_{wi}. The largest variation was for Rørdal chalk; increase in S_{wi} from 7.5 to 51% resulted in decrease in recovery from 67 to 30% of original oil in place.

Results for very strongly water wet chalk and zero S_{wi} were closely correlated with results for a wide range of other types of porous media. For the chalk cores, there was an overall tendency for imbibition rate to first increase with increase in initial water saturation and then decrease slightly with increase in S_{wi} above about 34%. For Berea sandstone the rate of imbibition decreased with increase in S_{wi} from 0 to 6%, was at a minimum for the range 6 to 15%, and then increased with increase in S_{wi} from 15 to 30%. These changes are ascribed to the net effect of initial water saturation and subsequent increase in water saturation on imbibition capillary pressure and resistance to flow of water and oil.

INTRODUCTION

Oil recovery by spontaneous imbibition is of special importance in fractured reservoirs, with low matrix permeability. Rocks which imbibe water spontaneously are at least partially water wet; the degree of water wetness is a dominant factor in the rate of oil recovery. Rate of spontaneous imbibition in porous media is basically determined by the net effect of the capillary pressure driving force and the opposing viscous resistance to flow. Characterization of wettability from imbibition measurements can be improved if other factors which affect imbibition rate are taken into account. These factors include, the rock pore structure, commonly characterized by permeability (k) and porosity (ϕ), the interfacial tension (σ), the oil and water viscosities (ℓ_o and ℓ_w) and relevant properties of the media with respect to flow of oil and water (k_{ro} and k_{rw}).

From examination of available imbibition data, the scaling law of Mattax and Kyte (1962) was modified to give a dimensionless time, t_D (Ma *et al.*, 1995).

$$t_D = t\sqrt{\frac{k}{\phi}}\,\frac{\sigma}{\sqrt{\mu_w \mu_o}}\,\frac{1}{L_C^2} \qquad (1)$$

Definition of the characteristic length, L_c, is based on the effect of sample size, shape and boundary conditions.

$$L_C = \sqrt{V_b \,/ \sum_{i=1}^{n} \frac{A_i}{l_{Ai}}} \qquad (2)$$

where V_b is the bulk volume of the core sample, A_i the area perpendicular to the ith imbibition direction, and l_{Ai} the distance from A_i to the no-flow boundary. A large body of data was closely correlated by this semi-empirical definition of t_D (Zhang *et al.*, 1996, Viksund *et al.*, 1996). In applying this scaling group to the highly complex process of spontaneous imbibition, careful consideration must, of course, be given to the differences between the basis on which the correlation was developed and the situation to which it is being applied. The formulation of Eq. 2 implies that imbibition is counter current. Direct evidence of counter current imbibition is provided by change in saturation distribution with time (Cuiec *et al.*, 1990**,** Graue *et al.*, 1994 and Viksund *et al.*, 1996).

A remarkable feature of the correlation is that the group $\sqrt{k / f}$, which is proportional to the microscopic pore size, gives close correlation of results for a range of porous media that include both natural and synthetic materials (Ma *et al.*, 1997). One purpose of this paper is to test the generalized correlation, identified in this paper as the reference curve, for a wider range of porous media including chalk from several sources. Chalk has very high porosity (often in the range of 40 to 50%) and very low permeability (about 1~10 md). There is also evidence that chalks can have organic or siliceous surface coatings which affect their wetting properties even with respect to brine and refined oils (Baldwin, 1988).

Thus a test of the general correlation between oil recovery by spontaneous imbibition vs t_D for chalks is of great practical interest. Chalk provides examples of extreme difference in pore geometry from sandstones. Except for the work of Hamon and Vidal (1986) on a synthetic media, aerolith, development of Eq. 2 is based on spontaneous imbibition from zero initial water saturation. In this paper, the effect of initial water saturation on imbibition for sandstone and chalk is investigated.

EXPERIMENTS

Properties of liquids and rocks used in this study are given in Tables 1 and 2 respectively. For chalk, in order to avoid the handling involved in measuring k_∞, values of k_w or k_o (see Table 2) were used in Eq.1. The decrease in t_D compared to use of the Klinkenberg gas permeability was less than 10%.

Establishing initial water saturation: Two closely related problems in core analysis are determination of the distribution of connate water in a hydrocarbon reservoir and reestablishing representative water saturations in the laboratory. Several methods of establishing S_{wi} were used according to the rock type and desired value of S_{wi}. In general, imbibition results established by different methods gave very close agreement.

Drying: Initial water saturations of 0% were defined from the core weight immediately after drying either in an oven or a desiccator.

Oilflood: For Berea sandstone, initial water saturations of 20% and higher were established by oil flooding. In oilflooding the chalk cores, because of their fragility, the net confining pressure (difference between the confining pressure and the downstream pore pressure) was kept below 10 bar. In establishing S_{wi}, the direction of flooding was always reversed. For the chalk cores, oil flooding at $\Delta P = 8$ bars gave initial saturations in the range 25-30%.

Porous plate: For establishing S_{wi} of 20% down to 2% for the Berea sandstone, the porous plate method was used with brine displaced by nitrogen. After achieving the desired S_{wi}, the core was saturated with refined oil under vacuum.

Adsorption: Very low initial water saturations (~0.5%) in Berea and Stevns chalk were established by adsorption of water on initially dry cores. This procedure is useful for comparing dry cores to cores which have been hydrated and contain surface adsorbed and capillary condensed water.

Evaporation: Achievement of very low initial water saturations in low permeability materials can often present difficulties (for example, in core analysis for reservoirs which have low water saturations). In order to establish low initial water saturation, some of the chalk cores were initially saturated with brine of some predetermined dilution. Water was then removed from the core by slow evaporation until the desired S_{wi} and brine composition was achieved.

Gasflood/drying: Water saturations of 25.1, 30.5 and 34.7 in the Stevns chalk were established by displacement of water with gas followed by a period of drying by gas flow through the cores.

Imbibition measurements: For the sandstones and Stevns chalk, cores at S_{wi} were suspended in degassed brine and change in weight of the core with time was recorded (Zhang *et al*., 1996). For all other chalks, volumetric imbibition cells were used.

Table 1 Liquid Properties

Fluid	Density g/cc	Viscosity cP	IFT (25°C), dynes/cm	Composition
RB-Brine	1.012	0.967	47.38	21.3g/l NaCl+0.6g/l $CaCl_2 \cdot 6H_2O$+ 0.1g/l KCl+0.2g/l $MgCl_2 \cdot 6H_2O$,
Soltrol 220	0.7975	4.24		Distillation cut: cleaned by flow through silica gel and alumina
CB-Brine	1.05	1.09	48.0	50 g/l NaCl+50 g/l $CaCl_2$
Refined oil	0.74	1.43		n-parafins: C9-C13

RESULTS AND DISCUSSIONS

Zero initial water saturation

A very good overall fit to the experimental data obtained for very strongly water wet Berea sandstone with zero initial water saturation is given by

$$R = R_\infty \left(1 - \frac{1}{(1 + 0.04\, t_D)^{1.5}} \right) \qquad (3)$$

where R_∞ is the maximum oil recovery by spontaneous imbibition. In this study, Eq. 3 was used as a reference curve. Results for spontaneous imbibition starting at S_{wi} = 0% for ten rock types with permeabilities ranging from 2 to 1500 md are presented in Fig. 1(a). Plots of normalized oil recovery, R_n, versus dimensionless time are presented in Fig. 1(b) plus the reference curve given by Eq. 3. Most of the imbibition curves fall close to the reference curve with approximately the same variation as found previously (Ma *et al*., 1995).

The Clashach sandstone exhibited slower imbibition with respect to t_D than all other sandstones tested to date. This can be ascribed to the effect on wetting of a surface coating of magnetite on the quartz grains (Buckley *et al*., 1995). Graue *et al*., (1988) observed an Amott wettability index to water, I_w, of 0.5. for Clashach sandstone.

The Seaton high porosity chalk (SH-0) showed significant induction time before imbibition began. This behavior probably corresponds to an initial wetting state which does not give immediate imbibition but which changes towards water wetness with time (Zhou *et al.*, 1996). Imbibition begins after 30 minutes. The same behavior was observed for a Seaton low porosity (SL-0) core and one other chalk also prepared at the same time as the SH-0 core.

Imbibition tests were repeated for two SL-0 cores (SL-0#1 and SL-0#2). After being formed by machining in a dry state, the cores were set in a vacuum desiccator for five days to reduce the possibility of contamination before making the imbibition tests. Spontaneous imbibition results for these two cores fell close to each other (results for SL-O#1 are included in Fig. 1(a)) and to the reference imbibition curve (see Fig. 1 (b)). It is concluded that the induction time and slow imbibition rates observed in some instances such as for SH-0 were caused by contamination. SH chalk could not be re-tested because additional samples were not available. The behavior of the SH-0 core and the Clashach cores are examples which demonstrate the usefulness of the correlation in identifying effects of wetting on imbibition rate even for cores which differ in permeability by three orders of magnitude.

Change in Initial Water Saturation:

Berea Sandstone: The effect of initial water saturation, S_{wi}, on imbibition rate and oil recovery for refined oil/RB-brine/Berea sandstone (strongly water-wet) is presented in Fig. 2. Test conditions for these experiments are summarized in Table 2. In all cases, the presence of an initial water saturation caused a decrease in imbibition rate with respect to the reference curve for $S_{wi} = 0\%$. The initial water saturations ranged from 0 to 30%. Final recovery (%OOIP) varied only slightly with S_{wi} (see Table 2). However, imbibition rate changed significantly with S_{wi} for $S_{wi} \leq 5.8\%$ (see Fig. 2a), was approximately constant for the range 5.8 to 15%, and from 15% to 30%, imbibition rate increases with S_{wi} (see Fig. 2b) towards the rate for $S_{wi} = 0\%$ (the reference curve).

Seaton Low-Porosity Chalk (SL): Results on the effect of initial water saturation, S_{wi}, on imbibition rate and oil recovery for refined oil/CB-brine/SL are presented in Figs. 3a and 3b. Test conditions for these experiments are summarized in Table 2. R_∞ is strongly dependent on S_{wi}. The initial water saturations ranged from 0 to 50%. Highest recovery was observed for $S_{wi} = 0\%$ ($R_\infty = 53.9\%$ OOIP) and lowest for $S_{wi} = 40.1\%$ ($R_\infty = 25.4\%$ OOIP). Apart from the results for SL-4 and SL-6, rate of imbibition was always higher than for the reference curve. Imbibition rate increases with S_{wi} in the range 10% to 34% (see Fig. 3a). For increase in S_{wi} above 34.4%, imbibition rate decreases (see Fig. 3b).

Rørdal Chalk: For refined oil/CB-brine/Rørdal Chalk, S_{wi} has a strong effect on ultimate oil recovery (see Table 2). Plots of oil recovery normalized with respect to maximum oil recovery by spontaneous imbibition vs dimensionless time are shown for $S_{wi} \leq 34\%$ and $S_{wi} \geq 34\%$ in Figs. 4a and 4b respectively. As for the SL chalk, there is an overall trend for imbibition rate to increase with S_{wi} up to about 34% and then decrease with further increase in S_{wi}.

Table 2 Summary-core properties, initial saturation (S_{wi}) and final recovery (R_∞)

Rock and Core No.	d (cm)	L (cm)	Lc	ϕ (%)	k_g (md)	k_w (md)	k_0 (md)	Brine	S_{wi} (%)	S_{wi} by	R_∞ (%OOIP)
Sandstones											
Berea (B)											
Berea1-0	3.82	7.59	1.27	22.9	1084			RB	0		55.8
Berea1-1	3.82	7.53	1.27	22.7	1056			RB	0.5	adsorption	56.2
Berea1-2	3.83	7.64	1.27	22.8	976			RB	1.6	porous plate	54.2
Berea1-4	3.83	7.69	1.28	23.0	996			RB	4.3	porous plate	55.8
Berea1-6	3.82	7.68	1.27	23.0	1087			RB	5.8	porous plate	52.6
Berea1-10	3.82	7.55	1.27	22.9	1030			RB	9.6	porous plate	51.9
Berea1-14	3.82	7.68	1.27	23.0	1088			RB	14.5	porous plate	53.0
Berea1-15	3.83	7.62	1.28	22.8	986			RB	14.8	porous plate	52.4
Berea1-20#1	3.82	7.64	1.27	22.9	1010			RB	20.0	oilflood	52.2
Berea1-20#2	3.83	7.58	1.28	22.6	1002			RB	20.0	porous plate	53.1
Berea1-26	3.82	7.61	1.27	22.6	1035			RB	25.7	oilflood	53.4
Berea1-30	3.83	7.68	1.28	22.3	998			RB	30.0	oilflood	54.0
Berea2-0#1	3.88	7.27	1.28	16.6	72			RB	0		53.8
Berea2-0#2	3.87	7.39	1.28	16.8	61			RB	0		55.8
Clashach-0#1	3.80	7.64	1.27	16.6	1500			RB	0		55.9
Clashach-0#2	3.80	7.66	1.27	16.4	1500			RB	0		56.1
Teensleep1-0	3.788	7.879	1.27	15.2	26			RB	0		43.8
Teensleep2-0	3.797	7.555	1.26	13.3	6			RB	0		41.2
Chalks											
Stevns -0	3.60	7.54	1.21	48.3	10.1			RB	0		76.8
Stevns -1	3.71	6.67	1.22	46.4	9.6			RB	0.5	adsorption	72.1
Stevns -25	3.69	7.74	1.24	48.5	11.9			RB	25.1	gasflood	58.5
Stevns -31	3.69	8.00	1.24	48.3	10.8			RB	30.5	gasflood	65.9
Stevns- 35	3.65	7.00	1.21	49.0	11.8			RB	34.7	gasflood	69.9
Rørdal											
Rørdal-0	5.05	7.97	1.63	45.8			3.2	CB	0.0		56.3
Rørdal-3	3.81	7.97	1.28	44.4		4.3		CB	2.7	vacuum	66.2
Rørdal-5	3.80	7.98	1.27	44.2		3.6		CB	5.3	vacuum	66.4
Rørdal-8	3.81	7.94	1.28	43.4		3.8		CB	7.5	vacuum	66.9
Rørdal-9	3.81	8.01	1.28	44.1		3.8		CB	9.4	vacuum	63.2
Rørdal-17#1	3.82	8.07	1.28	42.3		3.3		CB	17.4	oilflood	59.1
Rørdal-17#2	3.81	7.89	1.27	43.1		2.3		CB	17.2	vacuum	64.8
Rørdal-21	5.06	8.00	1.63	47.0		3.1		CB	21.3	oilflood	61.8
Rørdal-25	5.05	7.88	1.63	47.9		2.6		CB	24.9	oilflood	52.7
Rørdal-34	5.05	7.88	1.63	47.9		2.1		CB	34.0	oilflood	42.1
Rørdal-40	3.81	8.02	1.28	42.1		1.3		CB	40.3	oilflood	44.3
Rørdal-44	5.09	7.99	1.64	47.5		3.4		CB	43.7	oilflood	38.5
Rørdal-46	3.75	7.92	1.26	43.6		3.9		CB	45.8	oilflood	38.0
Rørdal-51	3.75	7.86	1.26	44.4		3.1		CB	51.3	oilflood	30.4
SL*											
SL -0#1	5.08	7.81	1.63	30.9			3.5	CB	0.0		52.5
SL -0#2	5.08	6.78	1.59	31.1			3.6	CB	0.0		53.9
SL -4	5.05	5.55	1.50	28.8		2.5		CB	3.9	vacuum	44.7
SL -6	5.04	6.32	1.55	24.6		1.3		CB	5.9	vacuum	44.7
SL -10	5.06	4.68	1.42	24.5		1.7		CB	10.1	vacuum	41.8
SL -15	5.05	5.81	1.52	26.7		1.8		CB	15.0	vacuum	38.7
SL -20	5.05	5.53	1.50	25.4		1.1		CB	20.2	vacuum	45.4
SL -21	5.04	6.86	1.58	27.5		2.1		CB	20.9	oilflood	37.6
SL-25	5.06	7.79	1.62	26.3		0.8		CB	25.1	oilflood	36.4
SL-34	5.06	7.79	1.62	26.4		0.8		CB	34.4	oilflood	35.5
SL-37	5.09	7.39	1.62	28.2		0.6		CB	37.2	oilflood	32.2
SL-40	5.05	4.38	1.38	33.8		0.7		CB	40.1	oilflood	25.4
SL-50	5.05	4.38	1.38	33.8		0.9		CB	49.8	oilflood	25.9
SH+											
SH-0	5.06	8.00	1.63	42.6			2.7	CB	0.0		43.3
SH-13	5.08	8.90	1.67	42.3		2.4		CB	13.4	oilflood	42.1
SH-14	5.10	7.10	1.61	37.0		3.0		CB	13.5	oilflood	46.2
SH-18	5.08	9.05	1.67	40.0		2.9		CB	18.4	oilflood	48.4
SH-19	5.08	8.90	1.67	44.0		2.2		CB	18.9	oilflood	42.2
SH-26	5.09	8.02	1.64	38.2		0.6		CB	26.4	oilflood	42.8
SH-27	5.09	8.02	1.64	39.2		0.6		CB	27.6	oilflood	43.7
SH-37	4.60	8.33	1.52	44.4		2.9		CB	36.7	oilflood	29.3
Dania-0	5.08	8.02	1.64	39.2			8.3	CB	0.0		47.7

*SL is Seaton low porosity chalk　　+SH is Seaton high porosity chalk

Stevns Chalk: The oil recovery for refined oil/RB-brine/Stevns Chalk is plotted in Fig. 5. S_{wi} was varied from 0 - 34.7%. There is a strong effect of S_{wi} on ultimate recovery (see Table 2). Plots of oil recovery normalized with respect to maximum oil recovery by spontaneous imbibition vs dimensionless time showed that the imbibition rate increased with S_{wi} up to 34.7%.

Seaton High-Porosity Chalk (SH): Normalized oil recovery vs t_D for refined oil/CB-brine/SH is plotted in Fig. 6. S_{wi} ranged from 0 - 36.7% and had a strong effect on ultimate recovery (see Table 2). Imbibition rate tended to increase with S_{wi}, but there were exceptions to the trend. Cores SH-13 and SH-14 had values of S_{wi}, k, and ϕ of 13.4%, 2.4 md, and 42.3%, and 13.5%, 2.9 md, and 37.0%, respectively. The scaled imbibition data gave earlier recovery for the higher porosity sample. This was also the case for Cores SH-18 and SH-19. Scaled imbibition for S_{wi} from 26 to 37% was significantly faster than for the reference curve.

SUMMARY

S_{wi} and final recovery by spontaneous imbibition

The three most extensive data sets were obtained for Rørdal, SL chalk and Berea sandstone. Except for two of the SL samples (Sl-0#1 and SL-0#2), each set of cores was cut from a single block of chalk or sandstone. Final oil recovery, R_∞, versus S_{wi} is plotted in Fig. 7a.

Berea sandstone shows only very minor changes in final recovery (% OOIP) with initial water saturation for the range studied. Thus, the displacement efficiency is essentially independent of the fraction of pore space initially occupied by water. Final recovery for Rørdal chalk is approximately halved with increase in S_{wi} to over 50%; above S_{wi}=10% the trend is roughly linear. The SL was more consolidated than the Rørdal chalk ($\phi \sim 28\%$ vs $\phi \sim 45\%$). Decrease in recovery from about 50% to 30% was also roughly linear. The trends shown by Rørdal and SL were not shown by the Stevns or SH (See values of S_{wi} and R_∞ listed in Table 2.) The Stevns chalk gave high recovery possibly because difference in pore structure or use of the RB brine.

For the SH, final recoveries were all within the range 42.1 to 48.2 except for the highest S_{wi} (44.4%) the recovery was 29.3%. These plugs came from different blocks and as for the Stevns chalk there are too few data points to identify a reliable overall trend between initial water saturation and final recovery.

The data shown in Figs. 7a are presented in Fig. 7b as final oil saturation by imbibition, S_{or}, versus initial oil saturation, S_{oi}. Berea sandstone and the SL (the compacted chalk) show similar trends. The Rørdal results are more scattered with a slight tendency for residual oil to increase with decrease in S_{oi} from 100% down to about 50%.

S_{wi} and imbibition rate

Increase in S_{wi} above 0% is seen to decrease imbibition rate relative to the reference curve for Berea sandstone whereas an overall opposite effect was obtained for the four chalks for which S_{wi} was varied. Curves giving the maximum increase in scaled imbibition rate for the four kinds of chalk all fell close together. Although empirical features of the correlation, i.e. effect of viscosity and viscosity ratio and the effect of variation in characteristic length, have not been tested directly for chalk, the observed trends in imbibition rate with respect to dimensionless time are generally consistent.

Values of $t_{D\text{-}ref}$ given by the value of t_D from the reference curve at R_n=50 %, divided by t_D at R_n = 50% from the experimental data are plotted against initial water saturation in Fig. 8. Increase in initial water saturation increases the relative rate of imbibition into chalk and for all four chalks, imbibition rate increased with increase in S_{wi} up to about 34%. Data for initial water saturations above 34% were obtained for Rørdal and SL chalk. Imbibition rate exhibited a distinct maximum at about $S_{wi} \approx 34\%$. Although the scaled rates of imbibition for Berea were low compared to chalk, imbibition rate increased with increase in S_{wi} over the range 5.8% to 30% (see Fig. 8).

The effect of increase in S_{wi} on imbibition rate is probably related to change in imbibition capillary pressure and mobility to water. Increase in S_{wi} and subsequent increase in water saturation by imbibition will decrease the capillary imbibition pressure which drives the imbibition process. At the beginning of imbibition, the relative permeability to water is very low and that to oil is very high. The mobility to water increases more readily during imbibition with increase in S_{wi}. Thus as S_w increases during imbibition there are opposing effects which determine the imbibition rate; the mobility of the water phase increases, but the capillary pressure which drives imbibition decreases.

From the form of the imbibition rate behavior, it is concluded that for chalk, the effect due to imbibition capillary pressure does not fall with S_{wi} as much as the effect of increased mobility to brine. There is an overall increase in imbibition rate up to about 34% S_{wi}. Above this value the rate of imbibition decreases. This may be because mobility to oil decreases with increase in water saturation.

Berea sandstone showed an overall decrease in imbibition rate with increase in S_{wi} indicating that the effect of decrease in capillary pressure is greater than that of increased mobility. Relative permeability to water in Berea sandstone (Braun and Holland, 1994) is generally lower (about 0.05 to 0.1 at residual oil) than for chalk (about 0.3 to 0.4 at residual oil), (Vidal, 1990). The lower water relative permeabilities for Berea sandstone compared to chalk are consistent with the overall differences in the effect of initial water saturation on imbibition rate.

The variation of imbibition rate with initial water saturation complicates the use of spontaneous imbibition data to characterize wettability. Although variation of initial water saturation for different rock types can result in about an order of magnitude change in imbibition rate, this is usually much smaller than the observed decrease in imbibition rate that can be expected with change in wettability from strongly to weakly water wet. Provided spontaneous imbibition of water occurs, scaled imbibition curves can be used to assess wettability for displacements under dynamic conditions for both chalk and sandstone.

CONCLUSIONS

1. Imbibition rate data for sandstones and chalks with extreme differences in permeability, porosity, pore structure, and for which there was no obvious departure from strongly water wet conditions, could be scaled with results falling close to a previously determined reference curve for zero initial water saturation.
2. Imbibition rate for strongly water wet Berea showed an overall decrease with initial saturation with the rate passing through a minimum.
3. Imbibition rate for four kinds of chalk tended to increase with increase in initial water saturation to a maximum at S_{wi} =34% and then decrease.
4. Differences in the effect of S_{wi} on rate of imbibition are ascribed to the net effect of reduction in imbibition capillary pressure and changes in relative permeability.

5. Final oil recovery for water-wet chalk decreased with increase in S_{wi}. Residual oil saturation was almost independent of S_{wi} (up to 30%) for Berea sandstone, but tended to decrease with increase in S_{wi} for chalk.
6. Scaled oil recovery vs time curves for spontaneous imbibition provide a useful approach to assessment of wettability for displacement under dynamic conditions for widely different types of weakly to strongly water-wet porous media.

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Nomenclature

A	area
k	permeability
l	distance from the imbibing surface to the no-flow boundary
L	length or characteristic length of core samples
n	number of surfaces available for imbibition
p	pressure
R	oil (or nonwetting phase) recovery
S	saturation
t	time
V	volume

Greek

μ	viscosity
ρ	density
σ	interfacial tension, IFT
ϕ	porosity

Subscripts

C	characteristic
D	dimensionless
i	ith direction of imbibition
n	normalized
o	oil
w	water
∞	ultimate (oil recovery) or infinity (Klinkenberg gas permeability)

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