MEASUREMENT OF CORE PROPERTIES USING A NEW TECHNIQUE – TWO ENDS OPEN SPONTANEOUS IMBIBITION

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ABSTRACT

Conventional oil/brine spontaneous imbibition experiments using cores with either the All Faces Open, or One End Open sample geometries give production/time curves where production varies approximately with the square root of time (almost exactly so for OEO imbibition). Thus only a single factor (made up of a group of unknowns including relative permeabilities) can be determined.

For Two Ends Open, with one end contacting the brine and the other end kept in contact with bulk oil at the same pressure, the behaviour is more complex because initially oil is produced counter-currently (and rapidly) at the brine face but this soon declines (approx with square root of time). Oil is then only produced co-currently at the oil end of the core and, depending on circumstances, its rate can increase or decrease with time. The split between co-current and counter-current production, and the two productions rates, depends primarily on the oil/brine viscosity ratio and relative permeabilities. If a pressure measurement is made then these relative permeabilities may be estimated.

Network models cannot yet model this experimental situation. A theory based on the piston-like displacement model has been developed. Experiments using homogeneous chalk samples initially fully saturated with mineral oil have been carried out using low and very high oil/brine viscosity ratios. Theory and experiment agree adequately and so several of the parameters involved in spontaneous imbibition can be estimated. In particular, it is found that the ratio of the NWP and WP relative permeabilities behind the front depends on the oil/brine viscosity ratio. Also, there is a significant capillary back pressure (or bubble pressure) at the brine face, a parameter not often included in analyses.

INTRODUCTION

One method of studying imbibition into fractured reservoirs is to conduct spontaneous imbibition experiments, most frequently under counter-current flow conditions (Morrow and Mason, 2001) because that is the expected natural boundary condition. In experiments, core plugs are short and gravity forces are negligible compared to capillary forces. Also, the matrix boundaries are either sealed or fully submerged in brine at all times. Many experiments under carefully controlled conditions have revealed a general correlation for the effects of multiple core and fluid parameters, Ma et al. (1997):

$$t_{\mathrm{D}} = Ct\sqrt{\frac{K}{\varphi}}\frac{\sigma}{\sqrt{\mu_{\mathrm{w}}\mu_{\mathrm{nw}}}}\frac{1}{L_{\mathrm{C}}^2} \tag{1}$$

The meticulous work of Fischer uncovered the effect of matrix boundary conditions; basically how the characteristic length factor L_c varied with core shape such as, All-Faces-Open (AFO), One End Open (OEO), Two-Ends-Open (TEO), and Two-Ends-Closed (TEC) (Mason et al, 2009). It also modified the effect of the fluid viscosity ratio (i.e. the square root term) (Mason et al, 2010a).

One interesting observation during TEO imbibition was the amount of oil produced from each open end face was usually unequal, even though the amount of water imbibed from each end face was equal and symmetric around the centre of the core (Mason *et al.*, 2010b).

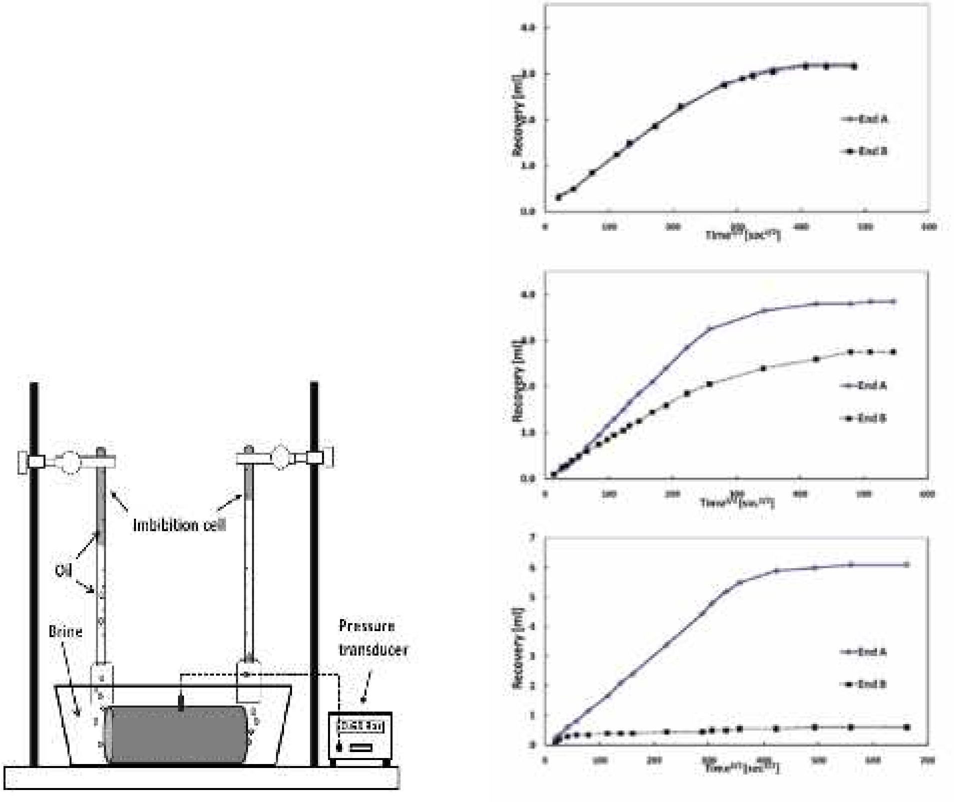

Figure 1. Experimental set-up for collecting produced oil separately from each of the open end faces in initially oil saturated Chalk cores with TEO boundary condition (left). The addition of the pressure monitor is optional (Mason *et al.*, 2010b). Results (right) showing asymmetrical oil production.

Asymmetrical production means that there has to be simultaneous co- and counter-current imbibition. The explanation lies in the need to overcome the capillary back pressure (CBP), $P_{c,o}$, at the outlet faces of the matrix (Parsons and Chaney, 1966). This pressure exists because the production mechanism at the open end faces is similar to a drainage process, and is determined by the largest pores at the surfaces (Li *et al.*, 2006, Mason *et al.*, 2009). Oil is produced as droplets (Unsal *et al.*, 2009). Even though the difference in CBP between the two open end faces is small, it can represent a large fraction of the pressure driving the flow of oil, especially if the viscosity of the NWP is small (air, for example).

Once developed, the technique for studying TEO imbibition can be extended to other situations, in particular TEO with one end in contact with bulk NWP. This gives combined co- and counter-current imbibition but with control over boundary conditions. Combined co- and counter-current imbibition has been recorded before (Bourbiaux, 1990). Depending on the viscosity ratio of the fluids, behaviour can be complex. If the viscosity of the wetting phase (WP) is high then most of the pressure drop occurs in the wetting phase and almost all of the NWP is produced co-currently. If the viscosity of the NWP is high, then most of the pressure drop occurs in that phase and a significant amount of the NWP is produced counter-currently.

SQUARE ROOT OF TIME BEHAVIOUR

In certain circumstances, variation of production with the square root of time is observed. This can be for both co- and counter- current imbibition and it is important to understand why, as this has caused confusion in the past.

1. *Two End Open capillary tube*

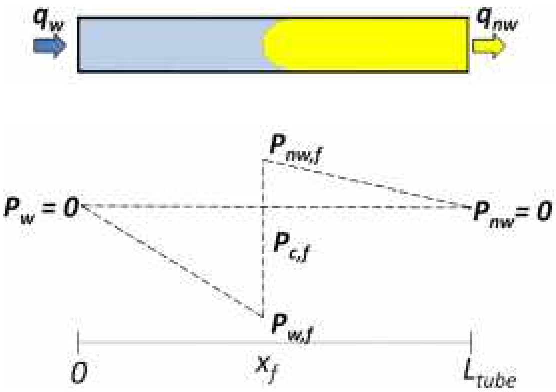

Figure 2. Wetting phase spontaneously displacing non-wetting phase in a capillary tube.

Washburn (1921) gave an analysis for co-current displacement in a uniform tube:

$$\mu_{\mathrm{nw}} L_{\mathrm{tube}} L - \frac{1}{2}\left(\mu_{\mathrm{nw}} - \mu_{\mathrm{w}}\right) L^2 = \frac{1}{8}\left(\frac{2\sigma}{r} + \Delta P_{\mathrm{applied}}\right) r^2 t \qquad 2$$

When the viscosity of the WP is high (or the viscosity of the NWP low, air, for example), then this equation simplifies and gives square root of time behaviour. However, it is only for the special case. If the two viscosities are equal then production is linear with time. And if the NWP viscosity is high then production actually accelerates as the WP advances down the tube. See Fig 2 and 3.

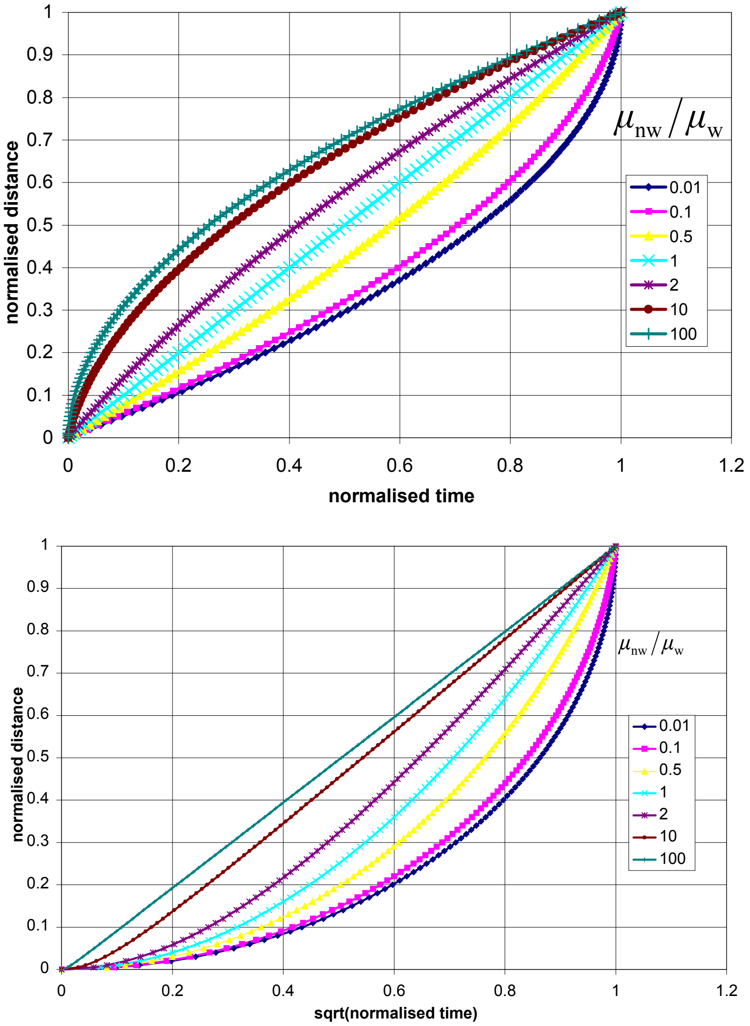

Figure 3. Normalised interface position as a function of normalized time in a single capillary tube with co-current displacement for various values of the viscosity ratio μ_{nw}/μ_w (upper). Note that decrease in the distance of advance of the wetting phase with $\sqrt{\text{time}}$ only happens when all of the resistance to flow is in the wetting phase (lower). If the viscosity ratio is unity, imbibition is linear with time. (Mason & Morrow, 2013).

2. *One End Open spontaneous imbibition*

One-End-Open imbibition also gives square root of time behaviour but this time imbibition is counter-current, and not co-current as in the Washburn analysis (see Schmid & Geiger, 2012, for example). The reason is that the resistance to flow varies linearly with the distance that the front has advanced irrespective of the viscosity ratio of the two liquids. Experiment confirms this, Fig. 4.

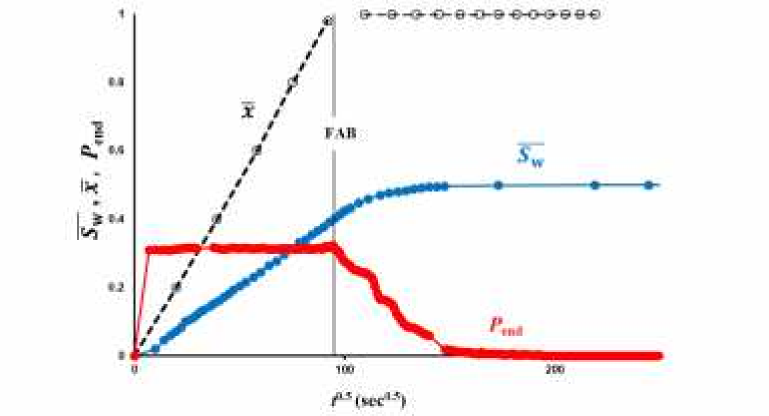

Figure 4. Typical experimental results for water displacing oil in OEO counter-current imbibition. Note the square root of time behaviour. S_w is the fractional saturation of total pore space filled by the invading wetting phase. x is the fraction of the bulk volume of the core (proportional to fraction of pore volume and also the fractional distance) through which the front has advanced as determined by electrical contact. P_{end} is the pressure measured at the dead end. FAB (Front At Boundary) indicates the time when the front arrives at the dead-end. (Li et al., 2006).

EXPERIMENTS

In the following experimental work, measurements were made of the amounts of oil produced from each end of a core with two-ends-open, but with one end in contact with brine and the other end in contact with oil. See Fig 5.

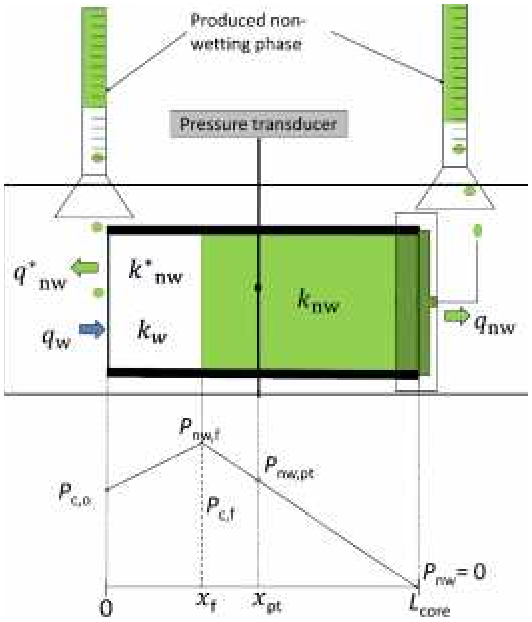

Figure 5. Schematic diagram of a two-ends-open core with one end in contact with wetting phase (WP) and the other end in contact with non-wetting phase (NWP). When the NWP viscosity is much higher than the

WP viscosity then production from both ends of the core continues until the front is near the NWP end of the core. In this flow regime, the pressure in the NWP just ahead of the front remains almost constant and equals the capillary pressure at the front.

The apparatus was designed so that brine could only enter one end of the core, but the oil could leave from either or both ends. Oil production always started with rapid counter-current imbibition at the end face in contact with brine. The duration and amount of counter-current production depends on the viscosity ratio of the two liquid phases. Cessation of oil production at the end face in contact with brine is caused by the capillary back pressure associated with the open face. If there were no CBP then counter-current production would not stop.

Once counter-current production ceases, production becomes purely co-current.

There are two extremes of behaviour depending on the viscosity ratio of the fluids. If most of the resistance is in the WP then counter-current production ceases early and behaviour is similar to Washburn behaviour (when the viscosity difference is included). If most of the resistance is in the NWP then co-and counter-current imbibition continue for most of the imbibition period.

Experiments were carried out with the two extremes of viscosity ratio. The rock used was chalk. Details are given in Table 1 below.

A photograph of the apparatus is shown in Fig 6

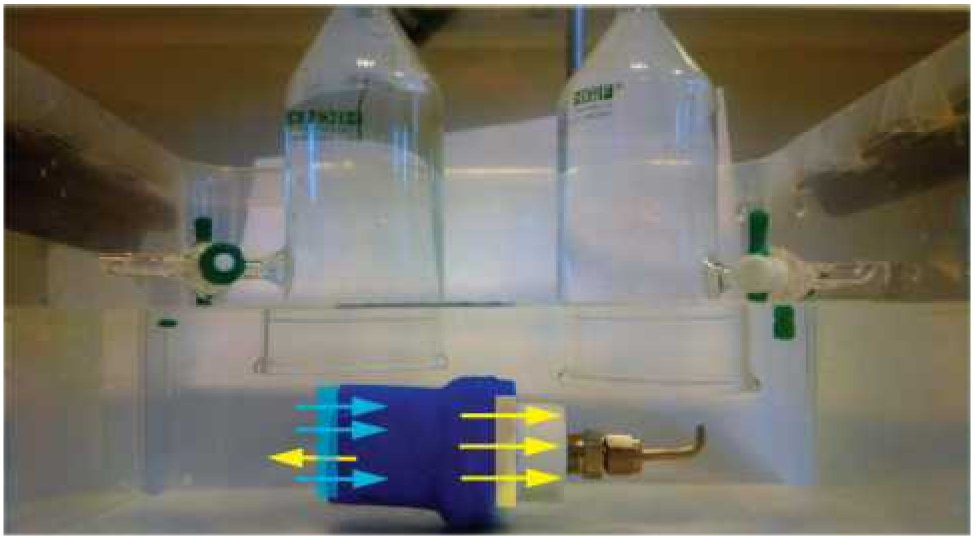

Figure 6. Image of the experimental setup. The blue-epoxy coated core was submerged in brine, with two open faces. The inlet open face was directly in contact with brine. The outlet open face was only contacted by oil and isolated from the brine with a custom-made end piece with a small tube outlet. Oil production was measured separately from each end face. In the experiments, core samples were fitted with pressure ports to record pressure response.

RESULTS

Results for predominantly co-current imbibition (low oil viscosity) are shown in Fig 7

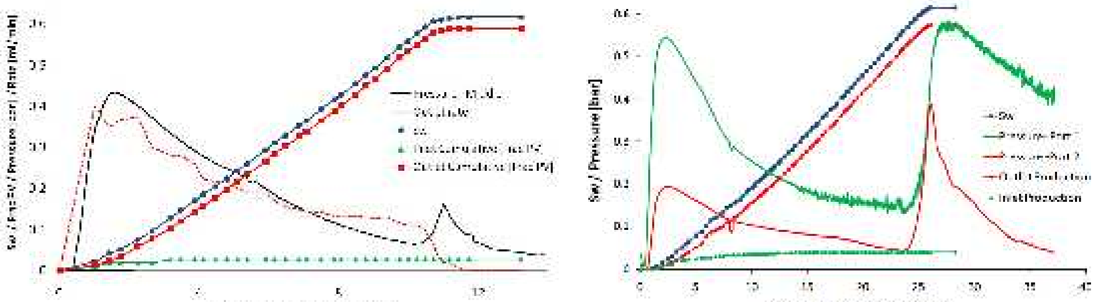

Figure **7.** Production and pressure history all versus square root of time (√min) for chalk core plug CHP5 (left) and CHP7 (right) during spontaneous imbibition. In CHP5 pressure was measured at the middle of the core (black line). There were two pressure tappings in CHP7. (Haugen et al., 2014).

Results when there is significant counter-current imbibition (high oil viscosity) are shown in Fig 8.

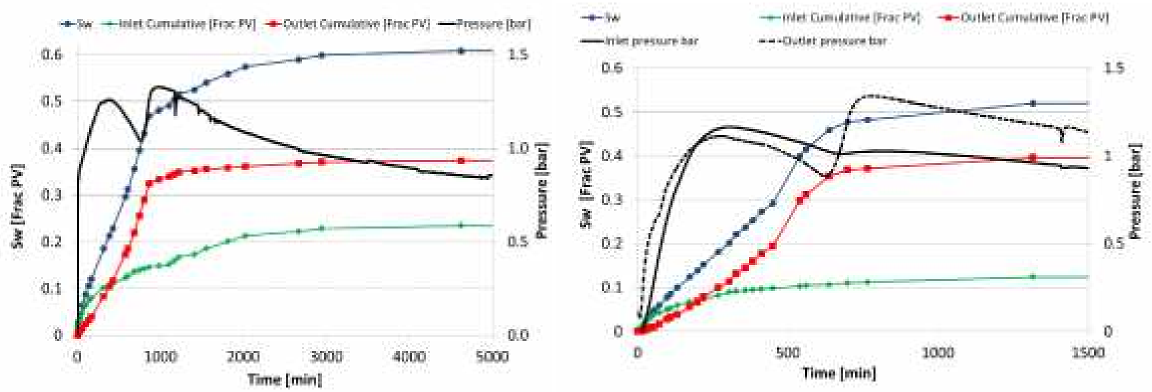

Figure 8. The experimental results for CHP11 (left) using chalk, high-viscosity refined oil and brine. The NWP viscosity was 137cP, the highest value tested. Note that these results are plotted on a linear time scale and that the total production curve is almost straight. Piston-like displacement finishes at about 900 minutes. Only the pressure recorded at the tapping furthest from the open face was successfully recording. Results for CHP25 (right) are for an 83.3cP oil.

THEORY

1. *TEO core, little counter-current production*

The purely co-current flow regime following cessation of counter-current flow can be approximately modelled as piston-like displacement. The analysis is almost identical to the Washburn (1921) analysis except that viscosities are replaced by μ/k 's, the capillary pressure at the front is the driving pressure, and there is not a 100% change in saturation.

$$\frac{\mu_{\mathrm{nw}}}{k_{\mathrm{nw}}} L_{\mathrm{core}} x_{\mathrm{f}} - \frac{1}{2}\left(\frac{\mu_{\mathrm{nw}}}{k_{\mathrm{nw}}} - \frac{\mu_{\mathrm{w}}}{k_{\mathrm{w}}}\right) x_{\mathrm{f}}^{2} = \frac{K P_{\mathrm{c,f}}}{\varphi\left(S_{\mathrm{wf}} - S_{\mathrm{wi}}\right)} t \qquad 3$$

The pressure at any point can be calculated from simple linear pressure drops behind and in front of the displacement front (see Fig. 10). $P_{\mathrm{nw,f}}$ falls as the front advances along the core.

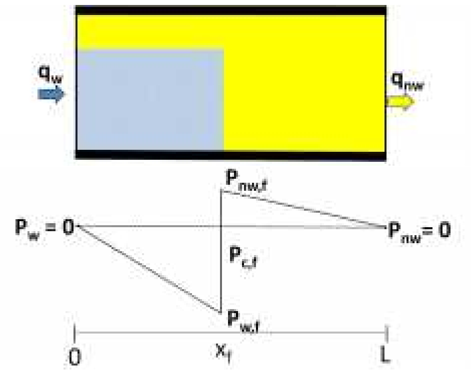

Figure 10. An imbibition front during co-current imbibition part way along a core together with the pressure distribution.

2. *TEO core with significant counter-current production*

When almost all of the pressure drop is in the NW phase the pressure distribution is as is shown back in Fig. 5. Two relative permeabilities are required, one for the counter-current flow of NWP, k_{nw}, and the other for the co-current flow of NWP, k^*_{nw}. The derivation of the full solution would be out of place here but the results are given below. Surprisingly, behaviour depends on a single parameter, *D*, which is a combination of relative permeabilities and pressures.

Let

$$D = \frac{k^*_{\mathrm{nw}}\left(P_{\mathrm{c,f}} - P_{\mathrm{c,o}}\right)}{k_{\mathrm{nw}} P_{\mathrm{c,f}}} \qquad 4$$

then an expression can be derived for the dependence of the normalised position of the front on time:

$$-\frac{(1-D)}{2}x_{\mathrm{f}}^2 + x_{\mathrm{f}} - \frac{D}{(1-D)}\ln\left(1+\frac{(1-D)x_{\mathrm{f}}}{D}\right) = \frac{K k_{\mathrm{nw}} P_{\mathrm{c,f}}(1-D)^2}{\mu_{\mathrm{nw}}\varphi(S_{\mathrm{wf}} - S_{\mathrm{wi}})L_{\mathrm{core}}^2}t \qquad 5$$

The normalised cumulative counter-current production is:

$$V^*_{\mathrm{nw}}(t) = -\frac{D}{(1-D)}A\varphi(S_{\mathrm{wf}} - S_{\mathrm{wi}})L_{\mathrm{core}}\left(-x_{\mathrm{f}} + \frac{1}{1-D}\ln\left(1+\frac{(1-D)}{D}x_{\mathrm{f}}\right)\right) \qquad 6$$

and the normalised co-current production is:

$$V_{\mathrm{nw}}(t) = \frac{A\varphi(S_{\mathrm{wf}} - S_{\mathrm{wi}})L_{\mathrm{core}}}{(1-D)}\left(x_{\mathrm{f}} - \frac{D}{(1-D)}\ln\left(1+\frac{(1-D)}{D}x_{\mathrm{f}}\right)\right) \qquad 7$$

To a first approximation, the pressure in the NWP just ahead of the front is constant. The pressure at the pressure tapping depends on the position of the front. Typical results are shown in Fig. 11.

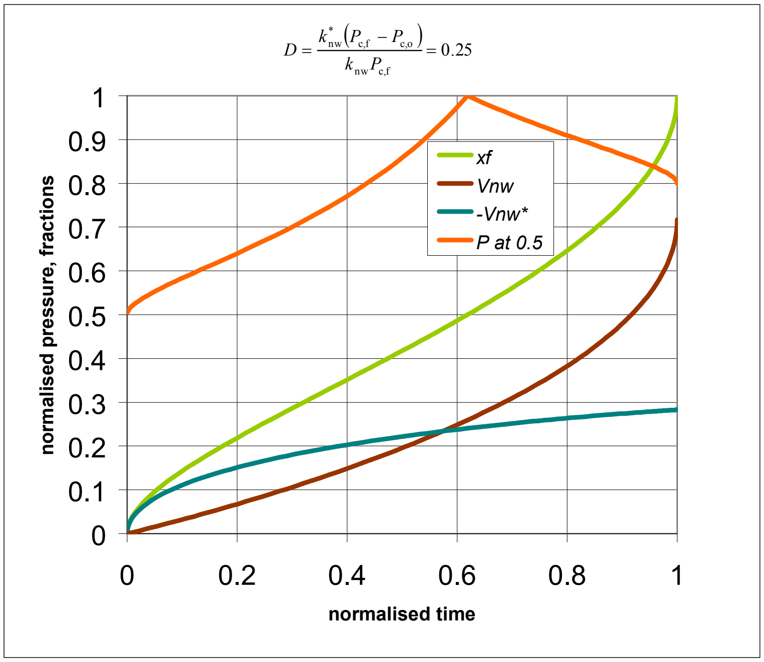

Figure 11. Typical values for co- and counter-current production with time. The two productions are expressed as fractions of the total pore volume. The pressure tapping is at the mid-point of the core and the maximum NWP pressure is recorded as the front passes the tapping.

DISCUSSION

The results of the experiments with the predictions of the theory superimposed are shown in Figs 12 (for mainly co-current) and Figure 13 and 14 (mainly counter-current).

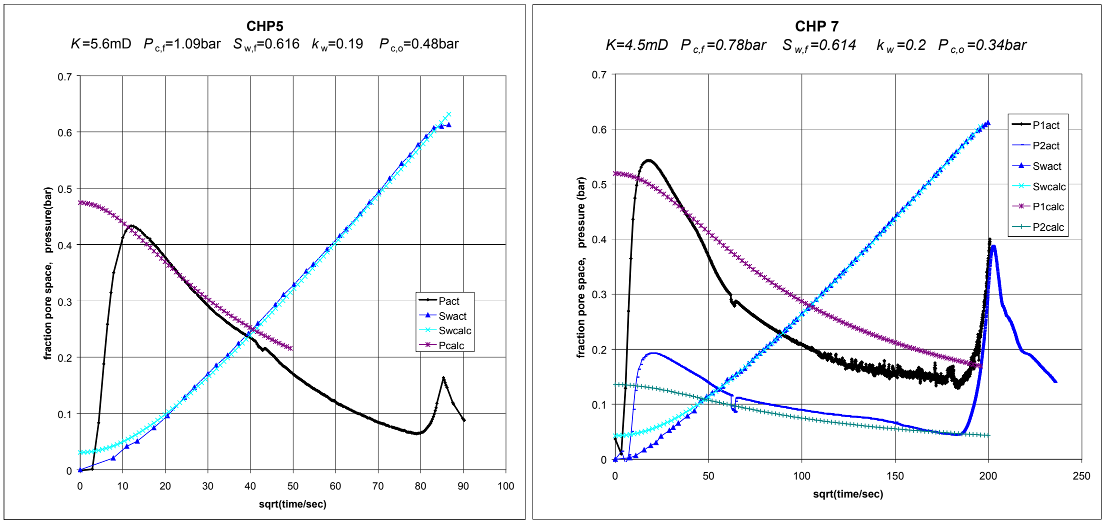

Figure 12. The results for co-current imbibition for CHP5 and CHP7 with the predictions of the theory super imposed. Once counter-current production ceases, co-current production is well predicted. Pressures are not well predicted at short time because the counter-current production speeds the advance of the imbibition front.

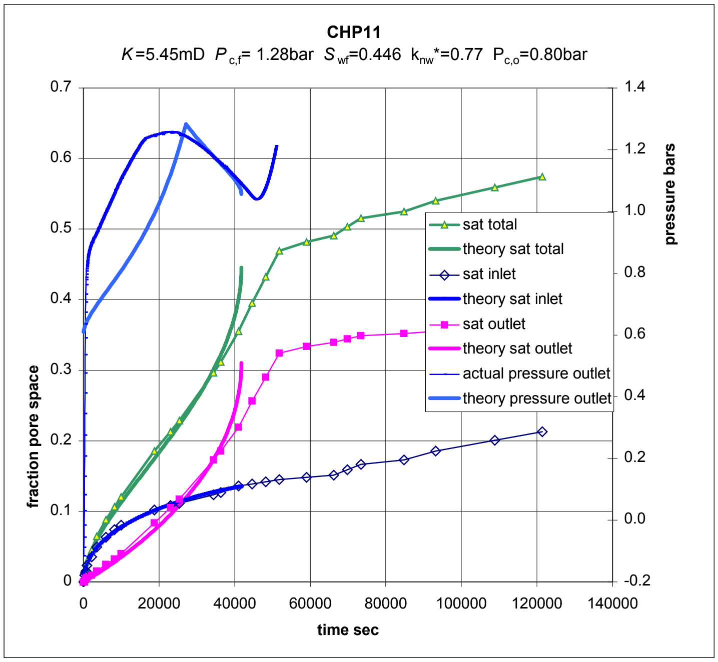

Figure 13. Results for 137cP oil compared to the best fit by the theory. Note that the theory does not fit very well as the front approaches the end of the core, and that the pressure only matches reasonably well.

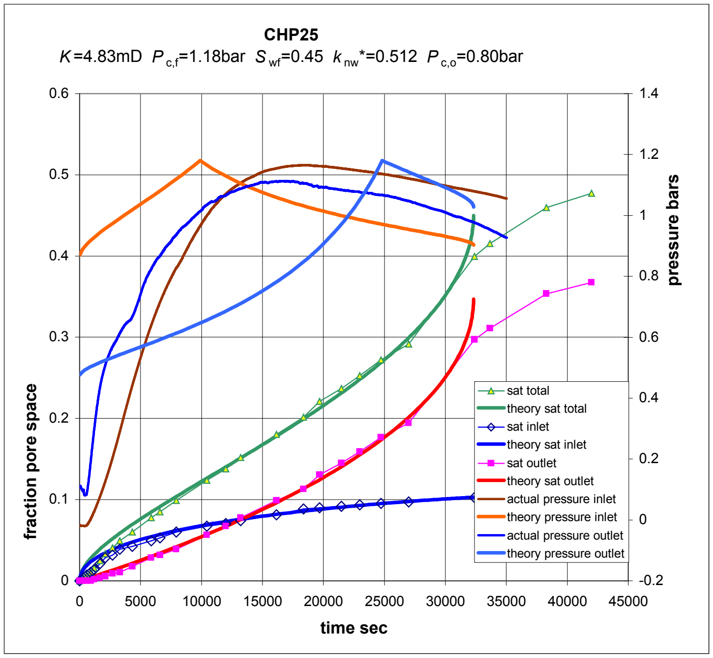

Figure 14. Results for 83.3cP oil compared to the best fit of the theory. Both pressure tappings and transducers appeared to be working but the fit to the theory for the pressures is poor.

A table of all of the significant results extracted by applying the theory is shown in Table 1.

Table 1. Rørdal Chalk

Core number	**CHP5 [a]**	**CHP7 [a]**	**CHP11**	**CHP25**
Length [cm]	6.0	14.5	6.1	5.75
Diameter [cm]	3.79	3.79	3.81	3.70
Porosity [frac]	0.494	0.467	0.466	0.458
Tapping 1 [cm]	3.0	3.0	1.38	1.58
Tapping 2 [cm	none	11.5	3.23	3.43
μ_w [cp]	1.09	1.09	1.09	1.09
μ_o[cp]	**1.47**	**1.47**	**137**	**83.3**
μ_o/μ_w	1.31	1.31	125.7	76.4
oil prod. at inlet	4.4%	6.4%	32.9%	25.1%
oil prod. at outlet	95.6%	93.4%	67.1%	74.9%
k_w	0.19	0.2	n.a.	n.a.
$P_{c,f}$ [kPa]	109.1	77.7	128	118
$P_{c,o}$ [kPa]	48	34	80	80
K [mD[	5.6	4.5 and 5.0	5.45	4.83
k_{nw}*	n.a	n.a	**0.77**	**0.512**
S_{wf}	0.616	0.614	0.446	0.45

It can be seen in the graphical results that, overall, the theory assuming a piston-like displacement front gives a reasonable fit to the experimental results.

For co-current imbibition the fit for production/time is poor for the first 10% of the production. This is because, in this region, counter-current production is still taking place, and so the theory is invalid. It is likely that the predictions for pressure are also suspect in this region for the same reason.

For counter-current imbibition, the theory predicts a sharp increase in the production as the front reaches the end of the core which is not seen experimentally. This is because counter-current production ceases before the front reaches the end of the core and the simple theory does not allow, or predict this. The pressure predictions are a poor fit to the experimental results, possibly because of the dynamic behaviour of the pressure measuring tappings.

CONCLUSIONS

In a theoretical study, Pooladi-Darvish & Firoozabadi (2000) identified that there could be co- and counter-current imbibition taking place simultaneously and they predicted that co-current imbibition would be faster and give higher recovery. The results in Table 1 confirm the latter prediction and also give estimates of the values of relative permeabilities. These should be taken as indicative because the experiments were probing the strengths and weaknesses of the methodology.

As expected, when the viscosity of the NWP was high, the relative permeability of the NWP behind the front was quite high – about 0.8 for the 137cp oil and about 0.5 for the

83cp oil. Basically, it has to be, otherwise there would be no significant counter-current production. In co-current production, the relative permeability to WP was about 0.2 at a WP saturation of about 0.6.

The pertaining pressures deduced from the theory show that the capillary back pressure at the brine face is significant, amounting to about half of the capillary pressure at the front.

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