INVESTIGATION OF PULSE INJECTION USING LABORATORY SPECIAL CORE ANALYSIS

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ABSTRACT

This study investigated the effects of pressure pulsing on laboratory SCAL measurements using an unconsolidated and consolidated sand, refined oils and γ-ray in-situ saturation monitoring (ISSM). Published literature presented at the 1999 European IOR Symposium has suggested that under pulsed flow conditions, Darcy's law may no longer be a valid description of single phase flow and that suppression of viscous fingering may also lead to significant improvement in oil productivity.

It was possible to reproduce the published single phase data, but our measurements showed that by careful measurement of the flow rate and pressure transients, the "enhanced" flow observed was an experimental artefact, both in the case of unconsolidated and consolidated core. Our measured differential pressures and flow rates, whether using pulsed flow or unpulsed flow, always obeyed a linear extrapolation as expected for Darcy flow.

Results from two phase measurements however, did show an effect when pulsing the injection fluid (brine in this case). When waterflooding the oil saturated sand, the pulsed waterflood was found to exhibit an increased brine phase mobility. It may be possible that the pulsing energy is sufficient on a pore level to overcome localised capillary pressure effects. A capillary pressure of +0.3 psi was measured for the unpulsed waterfloods at the point of water breakthrough, indicating water wet behaviour for these saturations. This capillary pressure at breakthrough was not observed for the pulsed waterflood (which would normally be indicative of a more oil wetting character). We observed earlier breakthrough and an increase in k_{rw} for the pulsed waterflood. The increase in brine relative permeability is an undesirable feature, and correspondingly the measured oil production was lower for the pulsed data. The ISSM data showed no evidence of suppression of viscous fingering and improved flood front stability.

In this study there were no obvious benefits from pulsing in either single phase or two-phase flow. In the field, there may be other benefits not related to the laboratory scale tests, such as the pressure wave causing changes to the near well reservoir architecture, or unblocking bridged perforations in high permeability sands.

INTRODUCTION

High amplitude, low frequency pressure pulsing was developed as a new workover technique and has been used in heavy oil wells in Alberta and Saskatchewan since October 1998. Work presented at the 1999 European IOR Symposium suggested that under pulsed flow conditions Darcy's law may no longer be a valid description of fluid flow in porous media [1-3]. In laboratory studies (with conditions representative of Canadian unconsolidated viscous oil fields) significant flow enhancement in single phase tests and suppression of viscous fingering in two-phase displacements were observed [4, 5]. This work is some of the first direct laboratory evidence supporting "vibrational methods" as a possible IOR technique.

The study was commissioned by the UK Department of Trade and Industry's Sustainable Hydrocarbons Additional Recovery Programme (SHARP), which assesses the potential of new and innovative IOR techniques that may be relevant to UKCS fields. The study we present in this paper set out to reproduce published results and to quantify whether Darcy's law is valid for one and two phase flow under conditions of pulsed injection.

REPORTED LITERATURE

Flow enhancements as high as 82% have been reported under pulsed flow conditions [4]. The experimental set up consists of a sandpack to which fluid is delivered from a constant head device and the produced fluid volume measured as a function of time. Pulsed flow was achieved with a manual squeeze or the impact with a rubber mallet on the Tygon^{TM} inlet tube, although in more recent studies by other workers a Consistent Pressure Source (CPS) is being used which repeatedly pressurises and depressurises a water inlet vessel with compressed air [6].

A key issue associated with the interpretation of the reported results is whether the pulsing action contributes a component of pumping to the system. In principle, the act of compressing the inlet pipe locally with a mallet could force a wave of fluid into the core and/or back into the constant head device where it would not be noticed. For typical reported results this would only need to be of the order of 0.001 to 0.01 mL per pulse. When the pipe relaxes (over a slower timescale determined solely by its physical character) fluid is drawn from the constant head device, in preference to the core, because of its lower flow resistance. Manual pulsing may also provide the opportunity to force additional fluid through the core if the pipe is progressively squeezed towards the core inlet using a "milking" action.

Davidson et al also report that viscous instabilities can be controlled through pressure pulsing [5]. The authors presented their observations from waterflooding a sandpack slab of approximately 35% porosity:

(1) saturated with 1600 cp heavy oil at a connate water saturation of 10%,
(2) 100% saturated with paraffin oil of 35 cp.

For the first test, Davidson et al. reported an unpulsed waterflood duration of around 45 minutes. A total production of 200 mL was measured (~4 mL/min) and oil production was reported as 35% (taken to mean 70 mL of oil from the 200mL of total produced fluids). A repeated test with pulsing produced around 200 mL in 38 minutes (~5 mL/min) with an oil fractional production of 90% (taken to mean 180 mL of oil). Similar observations were noted for their second experiment, albeit at a much faster rate (6 minutes duration at around 60-100 mL/min). It is difficult to draw conclusions from this data without oil production data, however, the suggestion is that there is a significant improvement in sweep efficiency when pressure pulsing, even if the increase in total flow rate can be explained as a laboratory artefact.

Recent theoretical studies of oscillatory flow of droplets in straight and constricted capillary tubes [7, 8] have shown significant increases in flow, for both the continuous and droplet phases. In constricted tubes there is also the possibility of oscillatory flow overcoming trapping of droplets at constrictions.

SINGLE PHASE FLOW - METHODOLOGY

If additional pumping components are present as a result of pulsing, increased flow rates may be observed. The use of the constant head device ***will not*** ensure that the pressure drop across the core is unchanged. It is therefore not sufficient to examine only plots of fluid production against time alone. Any increase in effective pressure drop across the core also needs to be taken into account.

The frequency of pulsing used in the reported laboratory studies is of the order of 1 Hz, which is very rapid compared to the timescales for changes in reservoir flow. Therefore, in the first instance, it is useful to test whether any special physical phenomena that could occur during pulsed flow can be understood within a framework of time averaged quantities. The validity of Darcy's Law for pulsed flow has been carefully assessed by comparing the average pressure gradient and average flowrate in vertical sand packs and consolidated cores to determine an effective permeability k_{pulse} under pulsing defined by:

$$\int q(t)dt = \frac{Ak_{pulse}}{mL}\int \left(p_{in}(t) - p_{out}(t) + \Delta r g L\right)dt$$

where the pressure differential has been corrected for a zero flow offset. Evaluation of the flowrate integral is straight forward since it corresponds to the total volume of fluid collected during the flow test. The pressure integral is more difficult to evaluate because of the rapidly varying pressures at inlet and outlet, and requires a large data sample to achieve statistically accurate results. In particular, if the sampling frequency is not significantly higher than the pulsing frequency, the issue of beat frequencies in the pressure data needs to be addressed.

Pulsed and unpulsed data for a range of heads and pulsing methods has been analysed by performing a linear regression between the average flowrate and gravity head corrected pressure differential. The slope of the lines correspond to the conventional permeability and effective permeability under pulsed conditions, k_{pulse}.

Flow Circuits

Three variations on the constant head flow circuit were considered. All valves shown were open, except those in the core by-pass line (connecting core inlet to core outlet) and the annulus fill/vent on the pressurised coreholder (Figures 2 and 3):

- A flow circuit (Figure 1) which uncoupled flow effects from pulsing action so that both effects could be quantified independently. This was achieved by adding a second pump to a constant head flow circuit that operated as an independent closed loop, but delivering a pulse to the core inlet. The second pump could be used with a choice of pump heads, delivery rate and refill rate so that a range of pulse frequencies (and to some extent the shape of the pulse waveform) could be investigated.
- A flow circuit (Figure 2) where the pulsing pump actually delivered the pulsed fluid to the core, and flowing concurrently with the constant head injection fluid. The pulse is "carried" with the delivered fluid volume and may flow through the core or as back-flow through the constant head device (if the flow could not be dissipated completely via the core). Two balances and a small measuring cylinder were used to carefully record the flowrate through the core, the total delivered volume from the pulse pump and the delivery from the constant head device.
- A circuit (Figure 3) which allows the use of a manual, hand held pulser. This set up was used to reproduce the published pulsing technique and pressure transients [4, 5] and compare with the first two mechanical pulsing methods.

SINGLE PHASE FLOW MEASUREMENTS

A total of over 60 tests were undertaken, which explored a wide range of variables including:

- Three constant heads (rates) with pulsed flow and unpulsed flow.
- Two fluids with different viscosities (dekalin 2.5 cp and light paraffin oil 25.5 cp) with pulsed flow and unpulsed flow.
- Variable pressure pulsing frequencies (0.2 Hz, 0.4 Hz, 1.0 Hz and 2.0 Hz).
- Pulsing device without flow, with flow and manual pulsing (by hand).
- Change in rock type (100 mD consolidated sandstone and 10,000 mD sandpack) with/without confining stress.

Unconsolidated sand with 2.5 cp oil

Results from tests on the sandpack with a 2.5 cp oil are summarised in Figure 4, which plots the average gravity head corrected differential pressure against the measured flow rate. In the pulsed measurements there is evidence for slightly reduced flowrates compared with unpulsed measurements, however, this is associated with slight reductions in pressure differential, such that linear regression analysis of the two sets of data shows that the pulsed and unpulsed data lie on lines with the same gradient (within statistical uncertainty). Therefore, the pulsed and unpulsed measurements show the same effective permeability, provided the actual averaged pressure differential is considered, rather than the nominal head for the system, as determined by the constant head device.

Unconsolidated sand with 25 cp oil

Results from tests on the sandpack with a 25 cp oil are summarised in Figure 5. There is some evidence for increased flow under pulsed conditions, however, this is associated with increased pressure differentials. As in the case of the set of measurements with the 2.5 cp oil, the pack behaves with the same effective permeability under pulsed and unpulsed flow conditions.

Davidson et al [4] recommend a rapid rise time, a slow decay time, and that a new pulse should be generated before the old pulse completely decays. This method of pulsing is said to generate a “synergetic pressure build up”. Tests using a manual pulsing method were also investigated. The system pressure transient from one manual pulse is shown in Figure 6. The average volume displaced by one manual pulse was measured to be 0.91 mL, which is significantly higher than that achieved by the mechanical pulsing pumps used in this study. A test was conducted with a series of approximately 270 pulses over 15 minutes. This lead to a very significantly enhanced flow rate of 81.4 mL/h, compared to 3.96 mL/h for the unpulsed measurement. However, the manual pulsing resulted in the inlet pressure rising to between 9 psi and 12 psi, with an average pressure drop of 10.4 psi. This additional data is shown in Figure 7, where it can be seen that it follows the extrapolated regression lines for the low rate data (both pulsed and unpulsed) perfectly. This demonstrates that Darcy Law is still valid for the average pressure drop and flowrate.

Consolidated sand with 25 cp oil

These measurements were made in consolidated sand (100 mD) using the flow circuit where the pulsing pump delivered the pulsed flow to the core. Results are summarised in Figure 8. This shows that significant flow enhancements were observed, however these always correspond to increases in the average applied pressure differential. Regression analysis finds the same effective permeability for pulsed and unpulsed flow, including the manual pulse data (within statistical error). Our results also showed that the consolidated core was much more attenuating than the sandpack. The pressure pulse, which is very evident at the core inlet, decayed along the core length of 25 cm to the extent that the outlet pressure pulse was barely detectable, unlike the pulse characteristic shown in Figure 6 for the 70 cm long sandpack.

Discussion

Enhancements in flow have been observed during pulsed flow, however, in all cases these corresponded to increases in the average pressure drop applied to the core, and the effective permeability for pulsed flow was the same as that found in unpulsed flow.

TWO PHASE FLOW MEASUREMENTS

Two phase flow measurements were made using the same sandpack used for the single phase flow studies. The sandpack was aged in excess of six months in stock tank oil (STO) prior to the first pulse injection study, and was known to be of intermediate/mixed wetting characteristic from in-situ saturation data. No Amott wettability tests were undertaken. The flow circuit used the pure, mechanical, pulsing method illustrated in Figure 1. γ-ray in-situ saturation monitoring was used to provide further information about any differences in flooding characteristics when using pulsed brine injection. Using this technique involved taking calibration scans with the sandpack fully saturated with doped brine (3%

NaI brine) and fully saturated with the light paraffin oil. Core scanning was undertaken throughout the study and the in-situ oil saturations calculated.

Waterfloods were conducted with the sandpack initially filled with 100% light paraffin oil to correspond to the conditions used in [5]. The waterflood procedure adopted for each test was identical. An initial low flooding rate of 4 mL/h (approximate frontal advance rate of 0.5 m/day) was followed by a high rate ("bump") flood at 400 mL/h.

The pack was restored at the end of each waterflood by mild, miscible solvent cleaning cycles and restoration to 100% oil saturation. Both the measurement of absolute oil permeabilty and the ISSM oil calibration scan showed the pack to be properly reconditioned in each case. The permeability was found to remain constant at around 10,000 mD.

Results

For the first two waterfloods (WF1 and WF2) no pulse was applied. For both waterfloods, an instantaneous pressure transient of +0.3 psi was observed at the point of breakthrough. This is indicative of water-wet behaviour at these saturations, and the small delay in breakthrough is attributed to water phase pressure build up to overcome the outlet capillary pressure effect (as the water displaces oil from the outflow end platen and flowlines). This pressure transient was not observed for the pulsed waterflood (WF3), which would normally be indicative of a more oil-wetting character. Figure 9 shows the breakthrough pressure transients, which was observed earliest in the case of the pulsed waterflood.

TABLE 1: Observed Breakthrough

Flood	Brine Injected at Breakthrough, PV
WF1	0.34
WF2	0.28
WF3 (pulsed waterflood)	0.25

To agree with the observations of Davidson et al [5] later water breakthrough would have been expected if the effects of pulsing are to stabilise the flood front and suppress viscous fingering. The γ-ray in-situ saturation data pre-breakthrough were heterogeneous, and close to breakthrough showed that the flood characteristics for WF2 and WF3 were very similar. When comparing WF2 and WF3, the pulsing showed no obvious effect on break-through time. Local zones that are more oil wetting than the rest of the sandpack are apparent, and initially the injected brine is unable to invade these areas (although WF1 did to some degree, resulting in the later break-through) until the continuous water phase pressure overcomes capillary pressure to match the oil phase outlet pressure. At later flood times, after water breakthrough, the brine is observed to access more pore space and the saturation distribution is more uniform. Figure 10 shows the in-situ, residual oil saturation following the low rate flood which also shows some degree of oil retention in the last 10-15cm of the core, but much more obvious is the local "inlet effect". This oil retention, which is probably a laboratory measurement artefact, may be evidence of viscous fingering and by-pass flow at the core inlet, until the flood front becomes more dispersed 5 cm or so into the core. At low flooding rates, this effect may suppress the measured brine permeability. The effect was removed by later high rate flooding.

Figure 11 shows the measured differential pressure and Figure 12 the corresponding oil production data for the three, low rate, waterfloods. The decline in differential pressure for the pulsed waterflood (WF3) is very noticeable. The oil production under pulsed flow is slower, with 0.65 PV produced after a brine throughput of 2.25 PV, compared to 0.78 PV and 0.74 PV for the unpulsed waterfloods 1 and 2 respectively. These results are consistent with an increased total mobility for the fluids, but with the water relative permeability enhanced compared to the oil relative permeability. The oil production and pressure drop data show that there is a long post breakthrough recovery of oil. This is characteristic of an oil- or intermediate-wetting core.

The data for 50 hours (approximately 1.7 pore volumes brine injected) has been replotted in Figure 13 to approximate “total produced fluids”, under conditions of constant pressure drop. This is possible by normalising the measured differential pressure data to the pressure at the beginning of the flood. Presenting the data in this way shows that it is consistent with the enhanced total flow observed and reported in [5], but not in terms of oil recovery.

At the cessation of low rate flooding, the rate was increased to 400 mL/h so that the viscous forces resulting from fluid flow would dominate over the pore scale capillary pressure forces. The measured differential pressure for each waterflood are shown in Figure 14. End point data for both the low and high rate floods (normalised to an oil relative permeability of 1 at 100% oil saturation) are summarised in Table 2 below:

TABLE 2: Waterflood, Measured End Point Data

Flood Rate	Observed Oil Production, PV			Relative Permeability, krw		
	WF1	WF2	WF3 (pulsed)	WF1	WF2	WF3 (pulsed)
Low	0.78	0.75	0.80	0.091	0.100	0.306
High	0.85	0.86	0.82	0.746	0.705	0.722

The brine phase relative permeability are shown in Figure 15. The JBN analysis data is presented to give an indication of the shape of the relative permeability curves (derived from the post-breakthrough production data given in Figure 12 in conjunction with the pressure data given in Figure 11 for a throughput of up to 3PV). The relative permeability is markedly increased for the pulsed waterflood at the low rate. It is evident from Table 2 that recovery at the low rate is higher for the pulsed waterflood but this is misleading since the pulsed waterflood was extended and continued with a brine throughput in excess of 6 PV. At throughputs of 2.3 PV and 2.9 PV for waterfloods 1 and 2 respectively, the corresponding recovery for waterflood 3 was 0.65 PV to 0.68 PV. The end-point S_{or} is highest for the pulsed waterflood (0.18 PV), there has been no recovery improvement.

CONCLUSIONS

The results from extensive measurements under single phase flow conditions have not found any situation where the flow rate could not be understood using Darcy's law based on unpulsed permeability data, provided that pressure data and flowrates are averaged. Where enhanced single phase flow seems to occur, this is actually a result of an increased inlet pressure due to an additional pumping action from the pulsing device. When evaluating pulsed flow studies it is essential to plot the production rate against average pressure drop, rather than just to look at cumulative production against time.

Our investigation of pulse injection under two phase flow was limited to three waterfloods, but adopted best SCAL practices including the benefits of γ-ray in-situ saturation monitoring. A primary objective was to observe ***significant*** benefits from pulsed waterflooding, which in the event, may have lead to a more substantial development programme. In contrast to the results of the single phase tests, measurable differences between unpulsed and pulsed waterfloods were found, consistent with enhanced flow for pulsed flooding. But our data showed a lower recovery for a given number of PV injection, (or for given time if the results are scaled to a constant pressure drop for the pulsed waterflood). In comparing our results with those reported in the literature it is important to recognise two differences:

1. Our study used a reservoir advance rate (~0.5 m/day). Capillary forces may therefore be more important than viscous forces, and the flood front is likely to be more stable (having the effect of suppressing viscous fingering).
2. A 70 cm long, cylindrical sandpack was used in this study, with a diameter of 2.5 cm, compared to the slab geometry in [5], with thickness of ~2 cm, but a width of ~30 cm. This may also affect the evolution of viscous fingers.

We concluded from our three waterfloods that:

- Pulsing ***did*** appear to change the character of the waterflood. The capillary exit pressure was reduced and the total mobility of the fluids was increased. Recovery for our pulsed waterflood was reduced. These changes are consistent with pulsing making the core behave as if it were more "oil-wet" than the unpulsed waterflood.
- Although at the laboratory scale capillary pressure effects are important, at the field scale capillary pressure is less of an issue. The results from high rate flooding gave similar pressure transients and recovery for ***all*** floods, showing that the effects of pressure pulsing are less noticeable (where capillary pressure forces are small). Since capillary pressure effects in the field will only be significant some distance away from the well (where viscous forces are lower) the pulse will need to be propagated some distance away from the well (pulse source).
- For our pulsed waterflood, pulsing was found to improve the injected brine phase mobility. For pulsing to be an effective IOR technique, the oil phase mobility must increase more significantly than the brine phase.
- The results from our laboratory study do not in any way question observations obtained in the field. The pulse workover technique may have significant benefits not related to laboratory scale tests, e.g. the pressure wave causing changes to the near well reservoir architecture, or unblocking bridged perforations etc.

NOMENCLATURE

A	Cross-sectional area of core	q	Darcy flowrate
g	Acceleration due to gravity	t	Time
k_{pulse}	Permeability	Dr	Density difference (oil-air)
L	Length of core	m	Viscosity
P_{in}	inlet pressure		
P_{out}	Outlet pressure		

ACKNOWLEDGEMENTS

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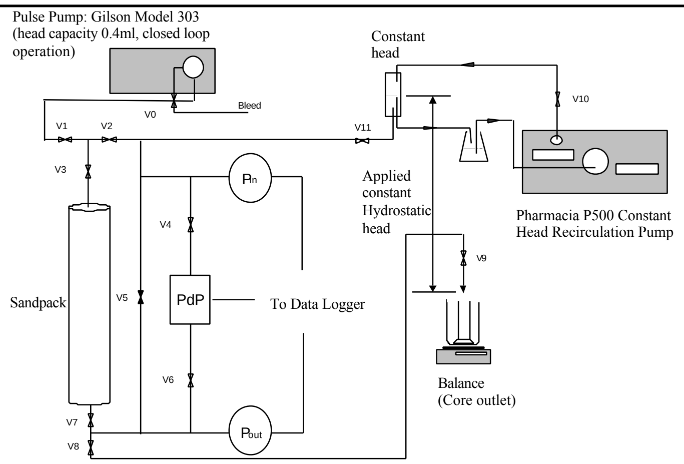

FIGURE 1: Flow Circuit with Uncoupled Pulse Device.

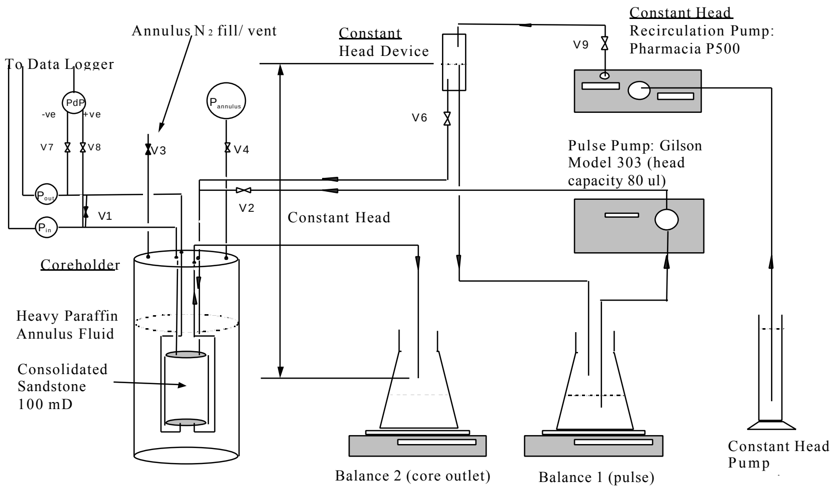

FIGURE 2: Flow Circuit with Delivered (Flow Through) Pulse.

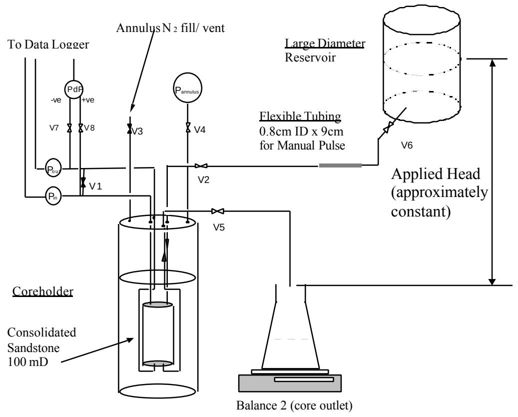

FIGURE 3: Manual Pulse Flow Circuit.

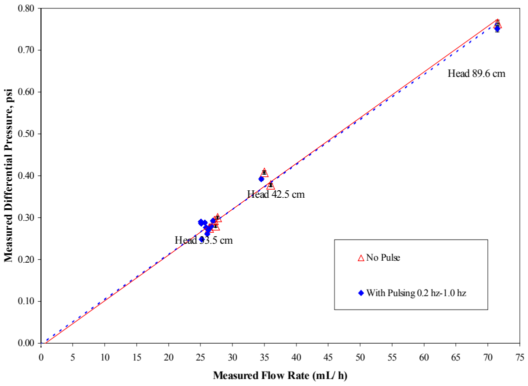

FIGURE 4: Measured Differential Pressure Vs Rate for 2.5 cp Oil.

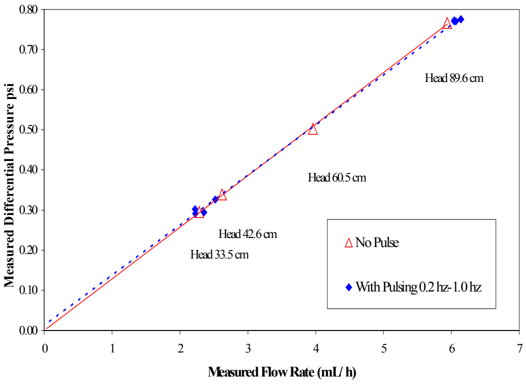

FIGURE 5: Measured Differential Pressure Vs Rate for 25 cp Oil.

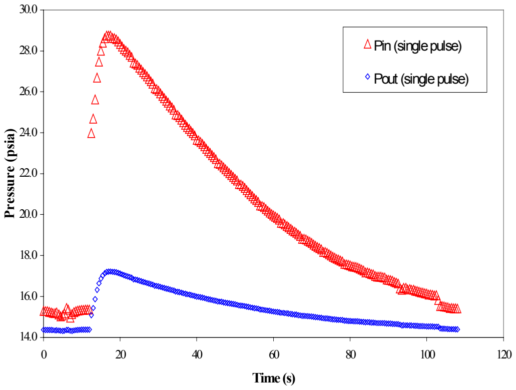

FIGURE 6: Pressure Transient from One Manual Pulse.

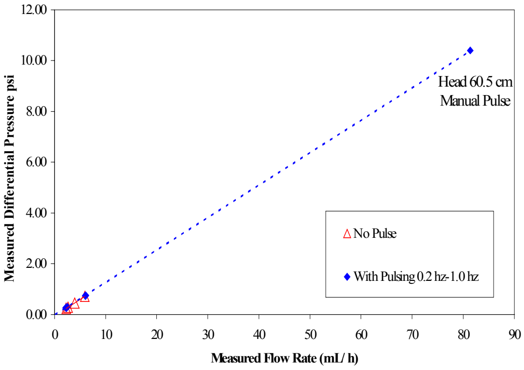

FIGURE 7: Differential Pressure Vs Rate, 25 cp, including Manual Pulse.

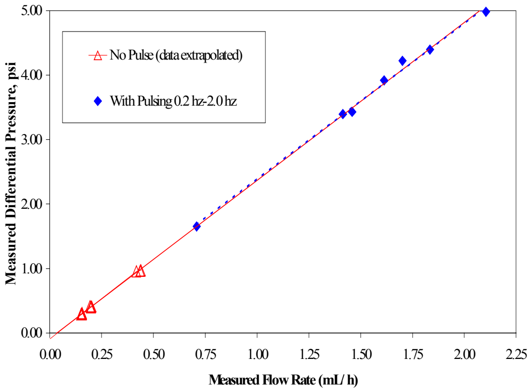

FIGURE 8: Differential Pressure Vs Rate for 25 cp Oil (using 100 mD Core).

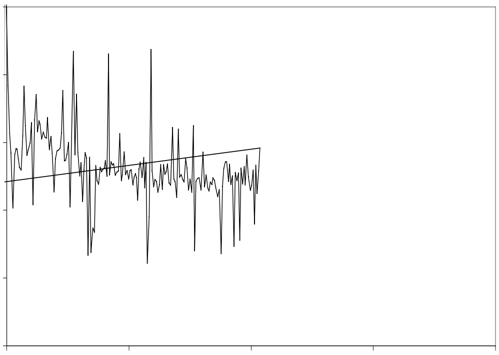

FIGURE 9: Breakthrough Pressure Transients

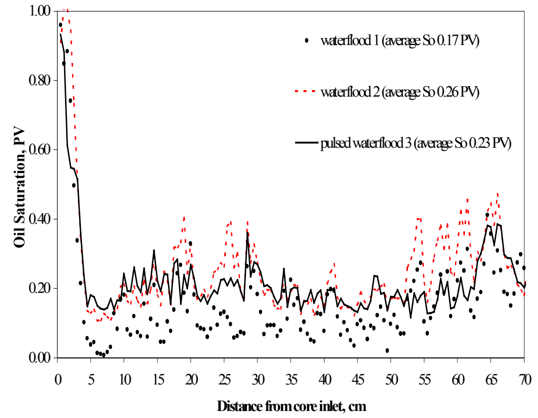

FIGURE 10: In-situ Oil Saturation and end of Low Rate Waterflood.

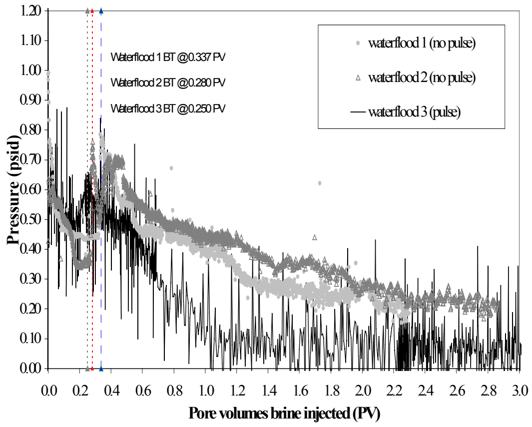

FIGURE 11: Measured Differential Pressure Low Rate Waterfloods.

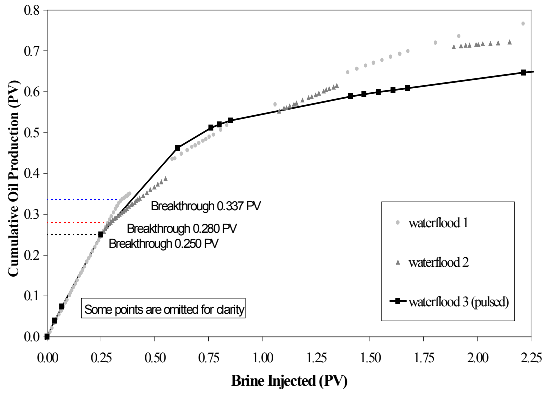

FIGURE 12: Oil Production Data Low Rate Waterfloods.

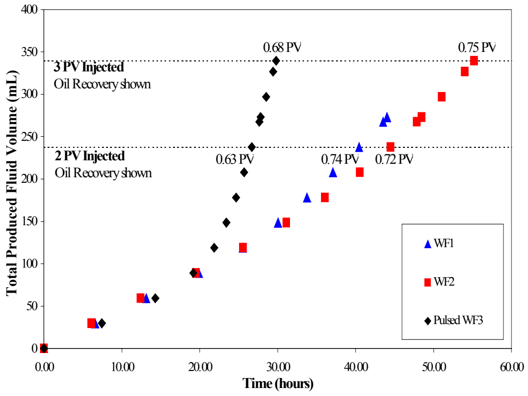

FIGURE 13: Total Produced Fluids Vs Time.

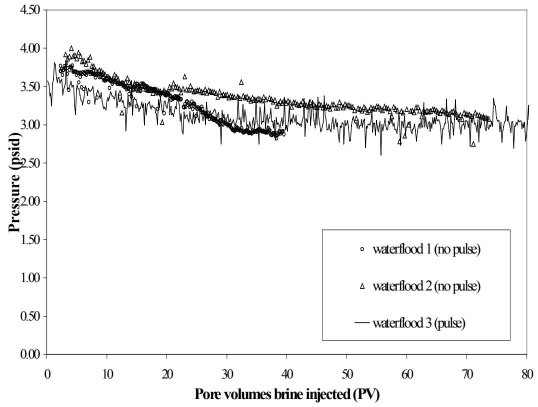

FIGURE 14: Measured Differential Pressure High Rate Waterflood.

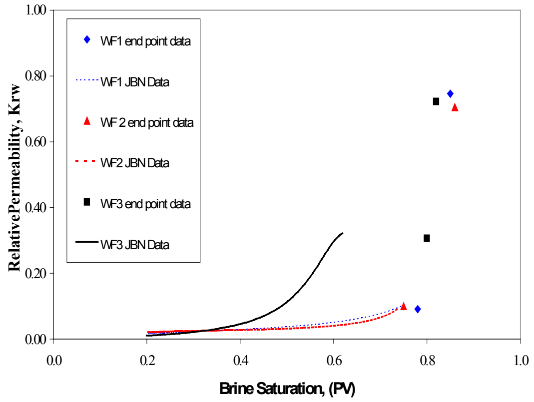

FIGURE 15: Calculated Brine Relative Permeability, k_{rw}.

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