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Increased Oil Recovery by Permeability Modification in High Permeability Contrast Slim Tubes

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Abstract

Biofilm and biopolymers produced from microbes have been shown to reduce the permeability of high perm streaks which can result in improved sweep efficiency. The rate of permeability modification is very reproducible but can vary depending on the specific treatments used. Our approach has been to inoculate the reservoir with a microbe that under the optimal nutrient conditions will express a biopolymer as a film, reduce the size of pore throats and reduce the apparent permeability. The microbe and the nutrients are tailored to the conditions of each reservoir thus giving MEOR the greatest chance for success. In this paper we describe the use of a high permeability contrast composite slim tube to demonstrate increased oil recovery using microbes that generate biofilms to reduce the permeability contrast and thus improve sweep efficiency. In this setup, three hydraulically constrained slim tubes – working as very long sand packs – were constructed from different sources of sand with a range of particle size distributions. Absolute and differential pressure transducers were used to monitor the pressure drop across individual slim tubes and across the composite configuration of the three slim tubes. Oil traps were located at the exit of each slim tube to measure the oil production from each tube. The permeabilities of the slim tubes against a high salt injection brine (TDS ~ 85,000 ppm) were measured to be 45, 4.5 and 2.6 Darcy. This presented a challenging system with a slim tube at a very high permeability that would need to be reduced by the MEOR treatment. Oil (viscosity of ~58 cp) was pumped independently into each slim tube to assure that each slim tube was at residual water saturation. The slim tubes were allowed to age before the start of the test. Once working in composite mode the flows of the injected brine and MEOR treatments were dictated only by the hydraulics of the composite slim tube. The produced fluids from all three slim tubes were sent to a single back pressure regulator. In the composite mode, oil was readily produced only from the high permeability slim tube during the initial (non-MEOR) flooding sequence. A salt tolerant microbe present in the target oil reservoir capable of producing biofilms and altering the permeability was inoculated into the composite slim tube. The inoculated microbes were batch fed periodically using a protocol that was scaled down from one that would be used in a field test. An increase in the pressure drop and corresponding increase in oil production from the lower permeable slim tubes was observed as a result of the treatment. This resulted in a dramatic increase in the recovery factor from the composite slim tube. This work is a continuation of tests described in earlier papers (SPE129657, SPE146483 and SPE159128 – references 4, 5 and 6).

Introduction

Much work has been done to understand the application of MEOR in an oil reservoir setting (1). Treatments include both huff and puff and interwell water flooding applications (2). The focus of this paper is the application of MEOR as an interwell treatment. In this application, the reservoir is inoculated with a selected strain and fed with an optimized set of nutrients in a manner that accomplishes the desired effect deep in the reservoir. A potential target reservoir must meet a set of criteria. The criteria we have developed are listed in Table 1. The fields must be under water flood (Table 1). Since the microbes live in the water phase, water flooding is used to

transport the microbes and nutrients into the reservoir. To support microbial growth, an efficient electron acceptor is necessary (Figure 1). In the anaerobic environment of a reservoir, oxygen is not considered a viable option due to corrosion issues and limited carrying capacity in the injected water. Addition of sulfate could encourage oil well souring by sulfate reducing organisms (10, 11). Therefore, we have restricted ourselves to a limited set of electron acceptors, concentrating mostly on nitrate. The pore throat diameter of the rock (Table 1) must be high enough to allow passage of microbes (3). The next three criteria in Table 1, temperature, salinity and pH, are the keys to determining the type and diversity of life seen in the reservoir. In most cases it is the combination of the temperature and salinity that are the most important for microbial life. The pH is often buffered to a neutral value due to natural minerals in the clays or cements of the rock. Since the MEOR mechanisms used do not affect the mobility of the oil in the reservoir, the viscosity of the oil is generally limited to the viscosity that can be effectively mobilized by the water flood. Down hole pressure is also a consideration. At extreme pressures only pressure tolerant microbes (piezophiles) will operate efficiently. Finally, the presence of high concentrations of sulfide can be toxic to life in the oil reservoir.

Table 1 – Criteria for MEOR applications.

Production mode	Secondary – fields under water flood
Metabolic Pathway	Anaerobic with restricted electron acceptor
Permeability	>30 milliDarcy
Reservoir Temperature	< 60 – 70°C (<140 – 160°F)
Salinity (injected and produced waters)	~<9% Total dissolved solids (TDS)
pH	5 – 9 (6 – 8 ideal)
Oil viscosity	<16 API (preferred)
Down hole pressure	<3000 psi (preferred)
Sulfide (H ₂ S)	~<5000 ppm

In Figure 1, the expression of a desired EOR function requires microbes (top of the triangle) a carbon source (lower left of the triangle) and an electron acceptor (lower right of triangle). It is the combination of a specific microbe, a carbon source and an electron acceptor that will lead to microbial growth and ultimately the expression of a function that is useful for enhanced oil recovery. In the treatments described below and in reference 4, 5, 6 and 7, the carbon source, the microbe and the electron acceptor are controlled in order to assure consistent and effective treatments. A non-oil carbon source is supplied that is soluble in water where the microbes live. Using the crude oil as the carbon source is problematic and has not worked in lab tests. Oil is not consistent in its composition, the metabolic rate using oil is limited due to the mass transfer limitations of getting the oil into the water phase where the microbes must live, and destruction of crude oil seems to be counterproductive to the very thing that EOR is meant to do, that is, increase oil recovery. The treatments described here do not use sulfate as the electron acceptor since that will lead to H₂S generation and oil well souring (9, 10). This is described in more detail in reference 5. Microbes that are selected for the treatment already exist in the oil reservoir. Consequently, the microbes are already adapted to the well environment. These microbes have been screened for their ability to express a specific useful EOR function. In the experiments described below, that function is the production of an exopolymer as part of a biofilm that reduces the pore throat size and the apparent permeability in watered out channels in the reservoir. As will be described below, it is necessary to augment or inoculate the reservoir in order to get a consistent expression of that function.

The need to inoculate the oil well with the preferred organism is illustrated in Figures 2 and 3. Population studies of authentic injection water are the basis for these illustrations. The native population before and after feeding the reservoir with only nutrients is illustrated in Figure 2. The relative abundance of specific microbes (Y axis) are plotted for each member of the native population before nutrients are added (blue bars) and after the native population has been allowed to grow on nutrients (red bars). The desirable microbe (“biofilm organism” that is circled) is a very small fraction of the microbial population. This is the typical situation we have observed in well environments. The growth of some microbes will be suppressed as a result of the nutrient only treatment -- for example, *Halomonas* on the left. The population of other microbes will be enhanced as a result of the nutrients (e.g. “unclassified”) including the microbe selected for its ability to produce the biofilm (circled). However, the desired microbe generally remains a small fraction of the population despite its enhancement with nutrients. Ultimately, this will lead to the wasting of nutrients for the growth of microbes that do not express the

biofilm forming function. Contrast this to Figure 3 that shows the changing microbe population using an inoculum. Here the biofilm producing microbe has been inoculated so that it dominates the population before nutrients are fed. The nutrients are designed to favor the biofilm microbe and to generate the biofilm. Consequently, this desirable microbe remains the dominant microbe in the population once nutrients are fed. Over time, there will be a population shift in the growth zone in the rock strata where the desirable microbe has established itself. This desirable population can be maintained by re-inoculating. Field data (6) shows no more than an annual re-inoculation will be required to re-establish the desired population.

Slim Tube set up

Core floods and sand packs are recognized as being one of the more realistic tests for measuring the effectiveness of enhanced oil recovery treatments in the laboratory. The slim tubes used in these tests are very similar to core floods. The rock taken from a well (or sand produced from a well) is mounted into a pliable container – typically an elastomeric tube that is chemically resistant to the oil and brines that will be pumped into and through the rock. The main differences between the slim tube described here and core floods are dimensions (slim tubes are very long and thin) plus the fact that a core flood uses an actual piece of rock while slim tubes use produced sand or crushed core. Specially designed end pieces seal the end of the rock cores or sand and allow brine or oil to be pumped uniformly into the face of the rock core or sand. The pliable container containing the sand or rock is placed inside a pressure vessel. This vessel is pressurized so as to put a constraining pressure onto the outside of the pliable container. The hydraulic pressure against the pliable container assures that the oil or water flows through the sand matrix and not along the outside of the sand next to the pliable container. For slim tubes, this constraining pressure also assures that the “loose” sand remains compacted and fines do not migrate and cause the permeability of the slim tube to drift. The hydraulic pressure also allows the slim tubes to operate at some back pressure inside the pliable container. Consequently, slight amounts of gases produced as a result of the microbial activity remain in solution. This assures an accurate determination of the apparent permeability during microbial activity.

Figure 4 illustrates a simple single slim tube set up. The slim tube is mounted inside a pressure vessel. The pressure vessel is filled with water that is pressurized by an external source of gas regulated to the desired constraining pressure. The hydraulic pressure can also be achieved using a syringe pump on a liquid filled pressure vessel. Pressure feed through ports at both ends of the pressure vessel allow tubing connected to the inlet and outlet of the slim tube to pass from the outside through the wall of the pressure vessel. Brine is pumped using a high pressure liquid chromatography pump or a high pressure syringe pump. A feed port is provided to the inlet line for periodic feeding of the slim tube. Pressure detection lines connect to the inlet and outlet of the slim tube to absolute and differential pressure transducers. The pressure drop across the slim tube is a measure of the apparent permeability of the slim tube. The differential pressure transducer and the difference in the absolute pressure transducers are used to determine this pressure drop. A precision back pressure regulator is mounted in the outlet line from the slim tube and is used to regulate the pressure in the slim tube. The pressure in the slim tube is always at least 20 psi lower than the hydraulic constraining pressure. Pressures and the flows are data logged 24 hours a day. The slim tubes described here are always in a horizontal orientation.

A variety of sands have been used to make the slim tubes. Figure 5 shows the particle size distribution for three of these sands. The particle size distribution (PSD) for these sand samples was measured by a Beckman Coulter LS13320. The LS13320 is an instrument which uses a laser diffraction technique to measure the PSD of materials using a wet module. The sample was split repeatedly with a chute splitter to obtain a small amount of representative sample. The aliquot was then dispersed in 20 ml of DI water and sonicated in ultrasonic bath for 1 minute. Some of this was introduced into the instrument until the desired concentration was reached. Each sample was analyzed in duplicate. The Fraunhofer diffraction model was used for the analysis of these materials. The stability and reproducibility of the measurements were very good.

The peak at the right of Figure 5 is for ocean sand (from EMD SX0076-30). The peak particle size is about 500 microns. Slim tubes made with this sand (see the discussion below) consistently showed a permeability of about 50 Darcys. The peak in the middle is produced sand from the North Slope of Alaska. The sand had been cleaned and some fines removed. The peak particle size is about 150 microns. Slim tubes made from this produced sand typically have a permeability of 7 Darcys. The left most peak was measured from crushed core sand from the Sparky sands in central Alberta, Canada. After crushing, some fines were removed. It has a very broad particle size distribution with a peak particle size of about 20 microns but with a significant fine particle size tail. Slim tubes fabricated from this crushed core sand consistently showed permeability of about 250 mD (see Figure 7 and 8, below). Core analysis of rock taken near the pieces used here had a permeability of about 160 mD. It is not just the peak particle size that dictates the resulting permeability of the sand in a slim tube. The

presence of a fine particle tail in the distribution will cause the apparent permeability of the slim tube to drop significantly. Slim tubes that span a range of permeabilities have been constructed by mixing a small amount of finer sand into coarser sand. An example of a mixture of sands is described below.

The sands were examined by X-ray powder diffraction to assure the presence of clays. Figure 6 shows the X-ray pattern for the produced sand from the North Slope of Alaska as described above. The X-ray powder diffraction data indicates a major phase matching the reference for SiO₂ (46,1045 - Quartz, >95%) – as expected. Trace phases indicated the presence of albite, kaolinite and halloysite. Other sands used in these slim tube tests also showed the presence of clays. However, the ocean sand lacks any significant clays (not shown).

Flow through the sand in the slim tube must follow Darcy's law for flow. It is important to assure stable Darcy flow through the slim tube before starting a flooding sequence. Darcy flow is assured if the pressure drop across the core or slim tube changes linearly with pressure. The ratio of the change in pressure drop to the change in flow rate ($d\Delta p/dq$) is a measure of the apparent permeability. Figure 7 shows run line pressure and brine rate data taken during a permeability test of a slim tube using the crushed core sand. The brine rate was measured from the change in weight of the produced fluids receiver. The variability in the flow is due to the low flows, the finite difference calculation needed to determine the flow and the action of the back pressure regulator. At this point in the flooding sequence, only brine had been pumped through the slim tube. No oil was present. The pressure was measured two ways – by the difference in the absolute pressure transducers (P1-P2) and using the differential pressure transducer (dp cell). The upper range of the differential pressure transducer was about 11 psi. The brine flow was stepped from about 1.9 ml/hour to 3.8 ml/hour to 5.7 ml/hour. At each step change in the flow there was a corresponding step change in both pressures. Pressures during each step were very stable. However, the differential pressure transducer could not provide an accurate reading for the highest flow since it was above its range. Figure 8 is a cross plot of the pressure drop and brine flow. The data points shown in this plot represent the average values taken at each step shown in Figure 7. The three "P1-P2" points are collinear – as they must be if there is Darcy flow. The slopes of the two lines are nearly identical. The intercepts to the lines represent the bias in the pressure drop measurement. The slopes correspond to about 250 mD once the geometry of the slim tube and viscosity of the brine is factored in. This slim tube (and others like it) was flooded with brine for an extended period of 3 to 4 weeks without any indication that the permeability was changing. This indicates that the fines from the crushed core were not migrating in the slim tube. This demonstrates that stable operation of hydraulically constrained slim tubes with permeabilities well less than 1 Darcy is possible.

These tubes are either operated independently as separate experiments, or run in parallel (composite slim tubes – described below) or run in series (to make a longer segmented slim tube – see reference 7).

After construction and pressurization, a flooding sequence is done to prepare the slim tube for the actual experiment. This flooding sequence can take as much as 1 to 3 months to complete. It is meant to condition the slim tube so that it resembles the target oil reservoir. The flooding sequence includes:

- Flooding with a real or synthetic injection water brine to assure a stable permeability, and to get the pH of the core or packed sand to the appropriate level. Proper pH is important for the microbiology and to assure that there is no inadvertent precipitation of calcium from hard brines.
- Flooding with degassed or dead oil until only oil is produced (slim tube is at residual water saturation). Prior to using the oil, great care was taken to dewater the oil by temperature cycling and decanting the water off as a separate phase. Dewatering agents were not used.
- Aging for about 3 to 4 weeks. This assures that the oil will wet the rock surface.
- It may be necessary to de-oil the slim tube to residual oil saturation by flooding with synthetic or real injection brine. Residual oil saturation is achieved when there is 100% water in the produced fluids from the slim tube. This was done for the "Reproducibility" experiment described below (Figure 9) and for the composite slim tube test. All tests described here were done at room temperature (25°C).

In the composite experiment described below, the slim tubes represent parts of the reservoir that span a range of permeabilities. The flooding sequence proceeds until the composite slim tube appears to be at residual oil saturation – that is the produced fluids are at 100% water cut. In reality, slim tubes with lower permeabilities are near residual water saturation. The flow path of the flooding brine and subsequent MEOR treatments were dictated only by the hydraulics of the composite slim tube. At this point the slim tube is "pre-inoculated" with live injection brine from the targeted oil field. This allows a background population of microbes to be resident in the slim tube. The slim tube is then inoculated with a microbe present in the well that was selected for its ability to produce a biofilm and reduce the permeability of the watered out channel. The volume of the inoculation is about one pore volume of a single slim tube. After a 3 to 7 day shut in period, injection brine flows and batch feedings are started. From this point on, the injection brine is constantly pumped into the slim tube for the rest of the

experiment. Batch feedings are scaled down from the protocol used in the field. It is important to assure that the nutrients are consumed in a growth zone inside the slim tube. That is, feeding must be done correctly for the nutrients to become bioavailable near the entrance of the slim tube and not at its exit. This concept is better illustrated in Reference 7. Even though the slim tube is inoculated before any batch feedings, most of the microbes remain in the slim tube and will consume the nutrients starting at the point where they are bioavailable. The biofilm will start to grow where the nutrients first become bioavailable. This "growth zone" as discussed in reference 7 will be stretched out in the reservoir since the nutrients are moving down the pressure gradient. The biofilm production responsible for permeability modification is not a fixed plug found over a short distance. Rather the permeability is modified over an extended distance in the reservoir. The biofilm production represents an integral effect across the extent of the reservoir where the nutrients are consumed. In a field application, an estimate of the areal extent of the high permeability channel or watered out channel as well as the water injection rate is used to size the treatment.

Typically the slim tube permeabilities are high. As a result these slim tubes represent a "worse case" scenario. If these can be "plugged" by a biofilm with a reasonable (economical) amount of nutrients, then there is a good chance for success in the porous rock matrix of the oil reservoir.

Reproducibility

Modifying the apparent permeability is reproducible. Figure 9 shows the relative change in the apparent permeability for 3 different slim tube experiments measured across about a year time frame and using 3 different sands. The change in apparent permeability is plotted on the "Y" axis as the ratio of the pressure drop relative to the initial pressure drop (dp/dp_0). The slim tubes were constructed from produced sands (including the one described above) plus additional fines. The experimental set up for each slim tube was the same (Figure 4). The diameter and length of each slim tube were about the same. Constraining pressures and flow conditions were similar. Different brine compositions were used. The brine reflected the composition of injected water being used at different oil fields being targeted for treatment. The permeabilities varied from 230 mD to about 2 Darcy. The MEOR flow conformance treatment used (MATRx™ FC-1) and feeding protocol were the same for all three slim tubes. Despite the significant change in the starting permeabilities, the relative change in the permeability with time appears to be very similar for the three slim tubes. The data shows about a factor of 4 reduction in apparent permeability here. Limitations in our equipment did not allow a test at higher permeability reduction factors. There is not a fundamental limitation in the treatments for permeability reduction. More recent tests using modified equipment (not shown here) have shown a permeability reduction factor of 10.

Composite slim tube test

The purpose of this test was to measure the effect of bio-plugging in a composite slim tube that represented reservoirs targeted for MEOR treatments. Slim tubes with very high permeability (ocean sand) and high permeability contrast (ratio of the high permeability slim tube to the low permeability slim tube) were used. The intent was to see if a slim tube with a permeability of ~40 to 50 Darcy could be made more restrictive to flow and produce oil from slim tubes connected in parallel to it that were about 10- 20X lower in permeability. This flow conformance treatment – MATRx™ FC-2 - was done after the slim tube had an oil release treatment done to it. This oil release treatment called, MATRx™ OR-1, reduces the residual oil saturation by changing the wettability of rock.

Tables 2, 3 and 4, summarize the properties of the slim tubes, brine and oil used in the composite slim tube tests. Ocean sand was used for the highest permeability slim tube (slim tube C). A mixture of crushed core sand (describe above) and produced sand from the North Slope of Alaska (also described above) was used for the slim tube with the lowest permeability. The slim tube with an intermediate permeability used produced sand from the Sparky Sands in Alberta. The permeability contrast is a high value of almost 20 -- as was desired. The porosities shown are approximate only. It is based on porosities measured gravimetrically when empty sand packs made from the same sands were initially flooded with brine.

The brine composition, Table 3, was developed to match the composition analysis of actual injection brine used in a target oil reservoir.

The oil, Table 4, from the target reservoir had a high viscosity that was cut by adding 15% by volume of mineral oil. A lower oil viscosity assured that there would be no pressure drop limitations as the experiment proceeded. However, the oil viscosity was still high enough that the oil was less mobile than the water – i.e., the pressure drop should decrease as water replaces viscous oil flowing through the slim tubes.

Figure 10 is a diagram of the setup of the composite slim tubes. Originally, each slim tube's pressure was controlled individually using precision back pressure regulators operating at the same pressure using a single source of nitrogen gas. It became apparent early in the test, that the back pressures for all the slim tubes could

not be identical using this scheme. Consequently, we had to switch to a single precision back pressure regulator for all slim tubes as shown in Figure 10. At the exit of each of the three slim tubes are oil traps. Produced oil from each slim tube collected in these traps in a vertical column that was measured throughout the course of the experiment. The % oil recoveries shown in Figures 12 and 13 were calculated from these measurements.

The three slim tubes were prepared in the manner described above. Figure 11 shows a plot of the pressure drop versus flow through one of the slim tubes that demonstrates Darcy flow and was used to calculate its permeability.

Table 2: Properties of the 3 slim tubes used in the composite slim tubes

Slim tube	Source of sand	Permeability, Darcy	Approximate porosity
A	20% crushed core Sparky sands / 80% Alaskan North Slope produced sands	2.6	30% (~40 cc)
B	Produced Sparky sands	4.2	30% (~40 cc)
C	Ocean sand	45.0	30% (~40cc)

Table 3: Brine composition used in the composite slim tube tests

Synthetic brine	
CaCl ₂ -2H ₂ O	7.73 gr/liter
KCl	1.00 gr/liter
MgCl ₂ -6H ₂ O	9.19 gr/liter
Na ₂ SO ₄	0.13 gr/liter
NaCl	61.70 gr/liter
NaHCO ₃	0.2 gr/liter

Table 4: Properties of the oil used in the composite slim tube tests.

	Crude oil as is	Oil used in test
Mineral oil added to cut viscosity	0%	15%
viscosity @25C	240 cp	69 cp
density, gr/cc	0.937	0.903
API gravity	20.2	25.2

Figure 12 shows the overall oil recovery from the composite slim tube and the approximate contribution of that recovery from each slim tube. Figure 13 shows the pressure drop across the composite slim tube plotted with the overall recovery. Just before day zero on these plots, the slim tubes had undergone brine flooding in the composite mode (but with individual back pressure regulators). At day zero, the slim tubes were treated with MATRx™ OR-1. This treatment reduces the residual oil saturation (reference 9). Immediately after this treatment, additional oil appeared to be produced from the 45 Darcy slim tube and a slight amount of oil was seen to be produced from the other two slim tubes. At this time, there was a transient spike in the pressure drop across the composite slim tube. It is likely that the mobilization of the viscous oil may be responsible for this transient spike in pressure. During this time, there was an unexpected oil production from the lower permeable slim tubes. After checking the pressure drops on each slim tube, it became apparent that the back pressure regulators were not fixing all the slim tubes to exactly the same pressures. At this point the pressure control for all three slim tubes was switched to a single back pressure regulator (as shown in Figure 10).

From day 10 to day 50, the slim tubes were flooded with synthetic injection brine (Table 3) to demonstrate stable operation and to assure that the slim tubes did not produce any more oil. As shown in Figures 12 and 13, there was no change in oil recovery and little change in the pressure drop across the composite slim tube.

On day 50, the composite slim tubes were treated with MATRx™ FC-2 microbes and nutrients and then shut in for 5 days. The inoculation was done in composite mode – that is, the microbes and subsequent nutrient feedings went where the water flowed. The inoculation procedure was identical to a field inoculation except scaled to the volume of the slim tube. After inoculation, the slim tubes were batch fed using a protocol scaled from field implementation procedures.

The overall oil recovery and pressure drop remained essentially constant from day 55 to day ~90. It appeared to take a long time for the permeability modification (biofilm formation) to show as an increase in pressure drop. During this time some adjustments were made to the slim tube operation in order to compensate for the larger than expected dead time in the front end of this composite slim tube set up.

By day 97 the pressure drop increased consistently and oil was produced from the low permeable slim tubes. No additional oil was produced from the 45 Darcy slim tube – as expected. By day 110, the 4.2 Darcy slim tube had stopped producing oil. The pressure drop also showed transient declines likely indicating that more viscous oil had been removed and replaced with less viscous water. The 2.6 Darcy slim tube continued to produce oil for another ~20 days. The pressure drop through this time period continued to increase as well. There were several transient drops in the pressure during this time. This is likely due to the production of oil and the oil being replaced with less viscous water.

By day 15 (before the MATRx™ FC-2 treatment) the approximate overall oil recovery was about 15%. About ~5 to 10% of this was due to the MATRx™ OR-1 treatment done on day 0. In contrast, at the end of the MATRx™ FC-2 treatment, oil recovery had more than doubled to about 35% overall recovery. This demonstrates the potential for increased oil recovery due to the re-direction of the flows to unswept lower permeability regions of a reservoir.

Conclusion

The composite slim tube showed a dramatic improvement in overall oil recovery when a biofilm treatment was used to modify the permeability of the highest permeable slim tube. The MATRx™ FC-2 treatment more than doubled the oil recovery. Despite the high permeability contrast in this composite slim tube set up, substantial oil was recovered from the slim tube with the lowest permeability. In contrast, the MATRx™ OR-1 treatment, that is designed to reduce the residual oil saturation, had much less of an impact on oil recovery – in part because this treatment affects only zones that are water wetted. In this case only one slim tube was affected by the MATRx™ OR-1 treatment.

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Figures

Figure 1: Triangle of microbial activity.

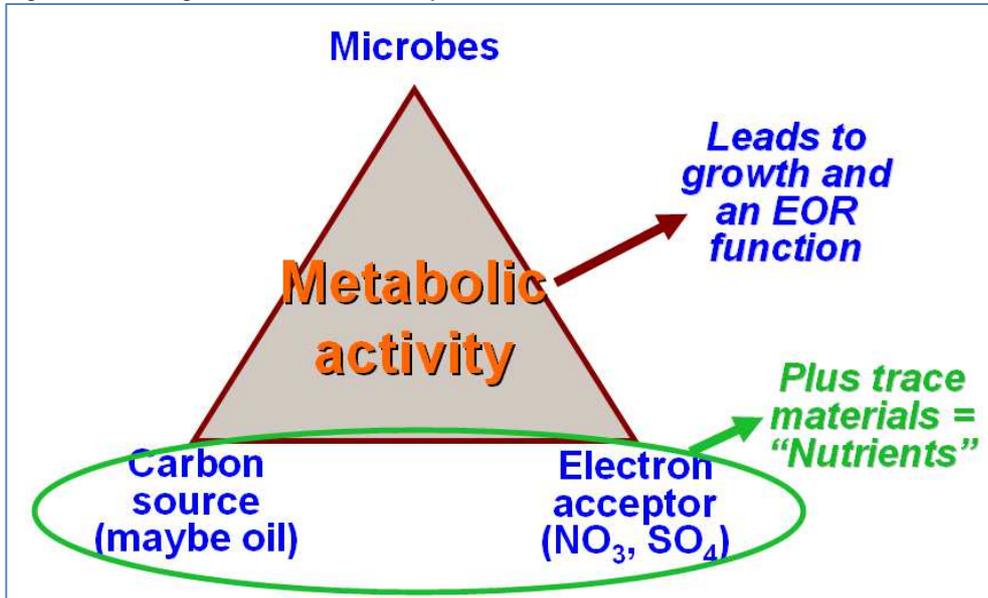


Figure 2: Changing microbe population as a result of feeding nutrients only.

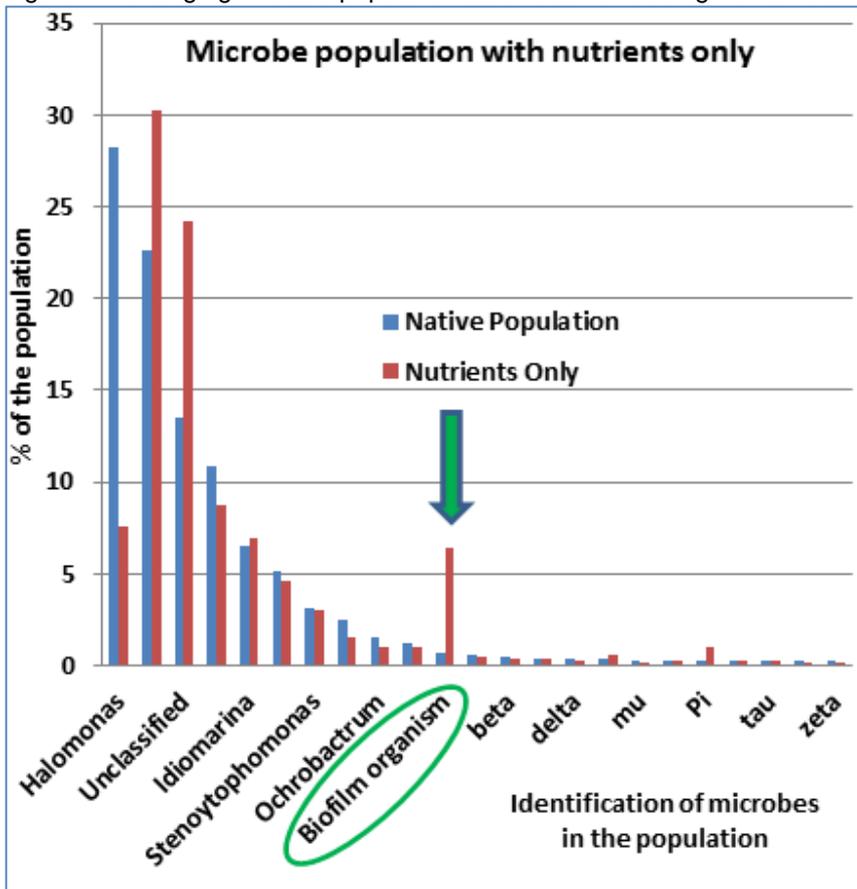


Figure 3: Changing microbe population as a result of inoculating and then feeding nutrients.

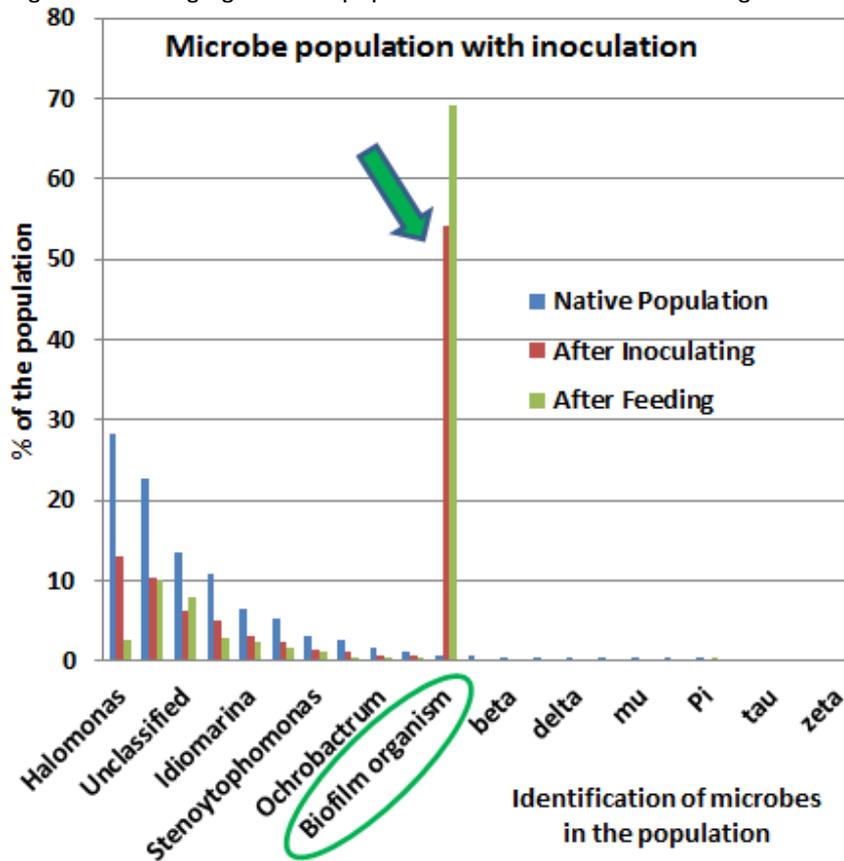


Figure 4: Single slim tube set up.

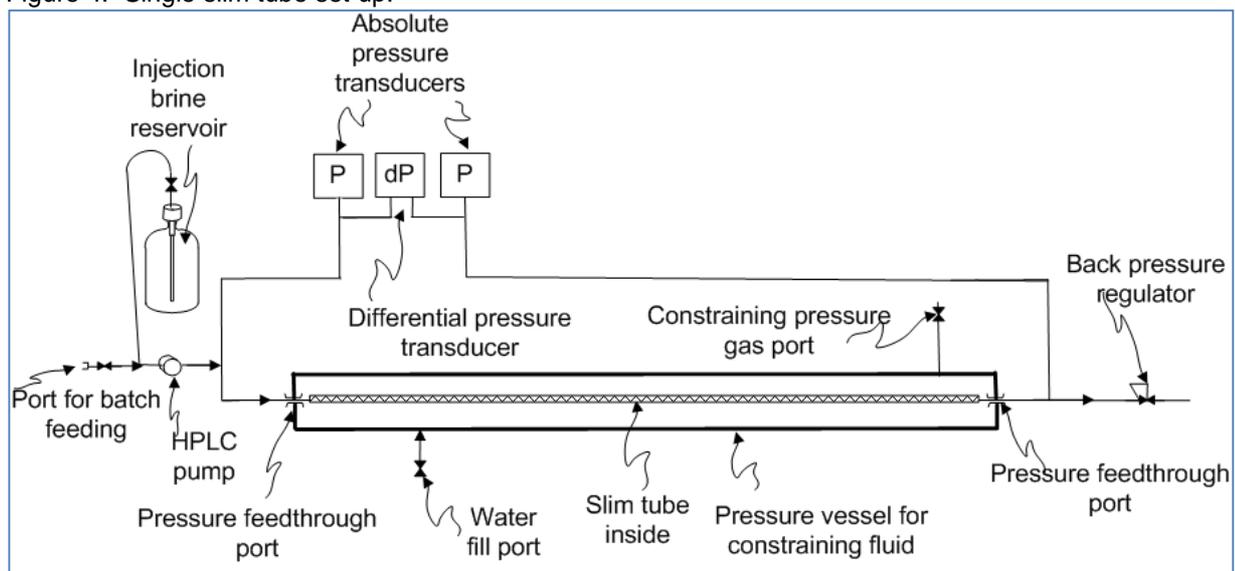


Figure 5: Particle size distributions of sands.

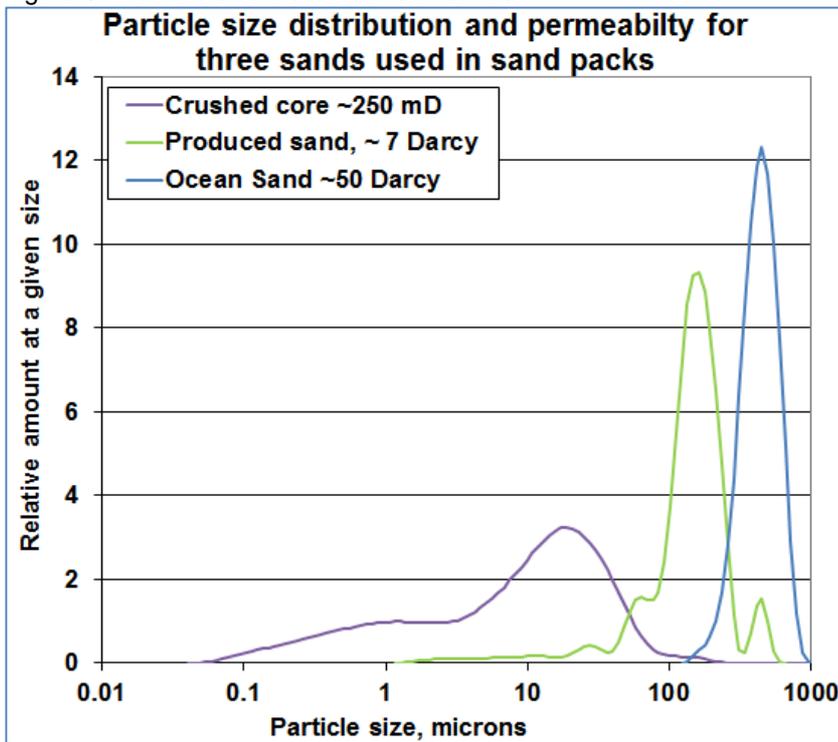


Figure 6: X-ray powered diffraction of the produced sand.

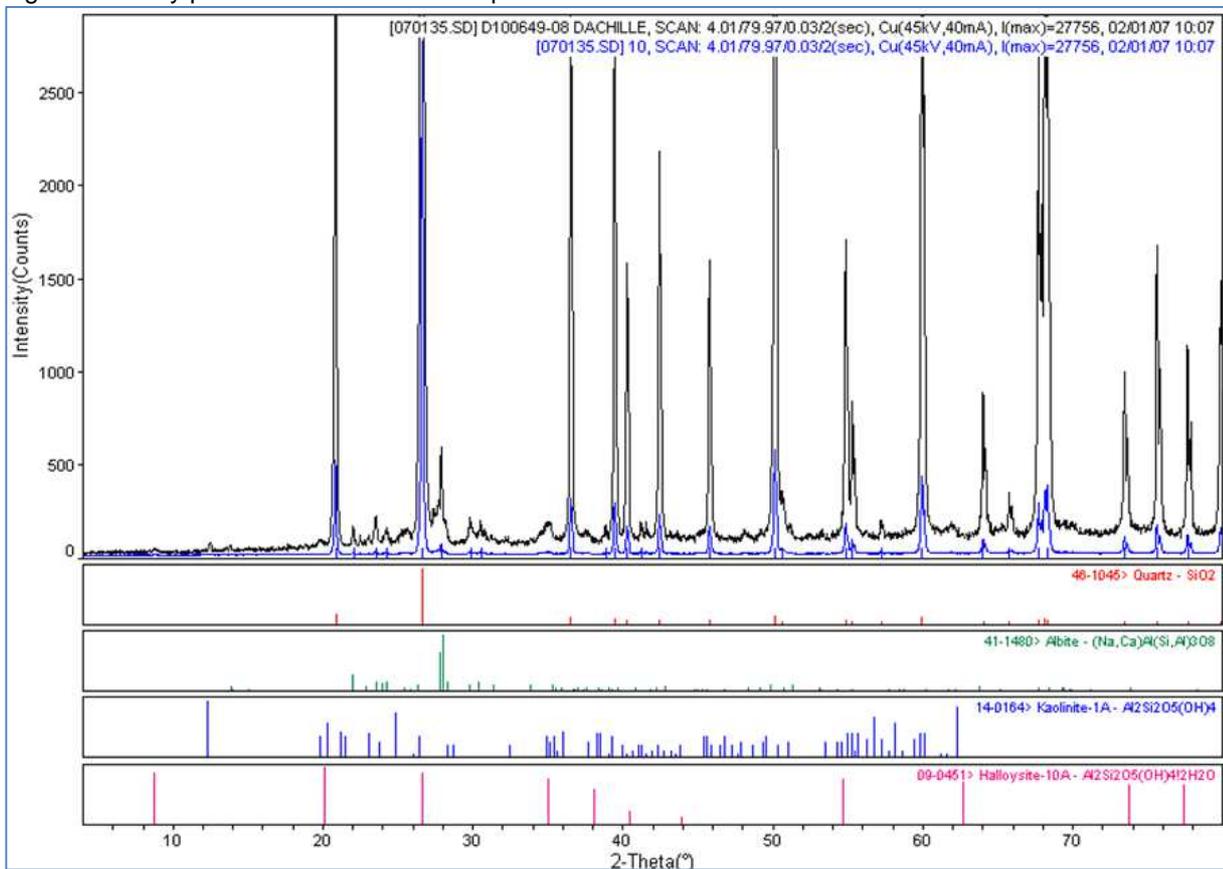


Figure 7: Pressure drop across and brine flow through a single slim tube.

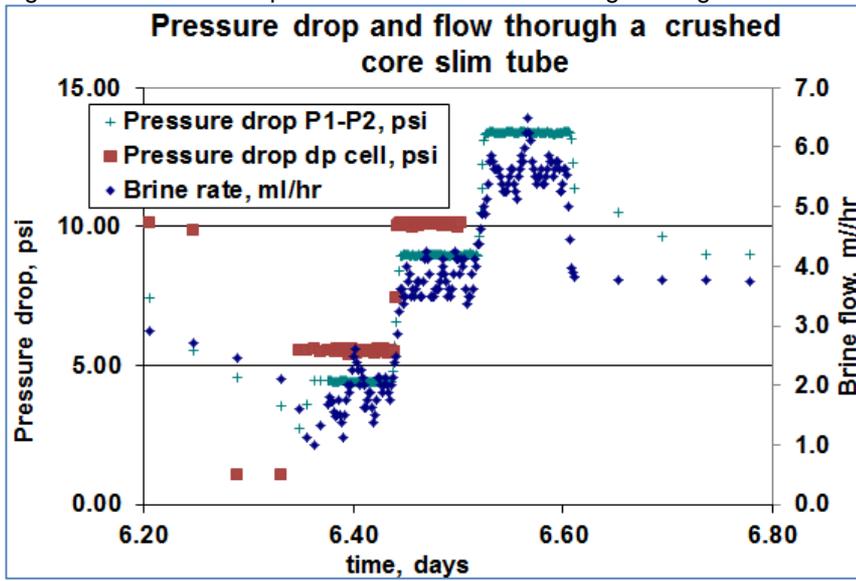


Figure 8: Cross plot of Pressure drop and brine flow

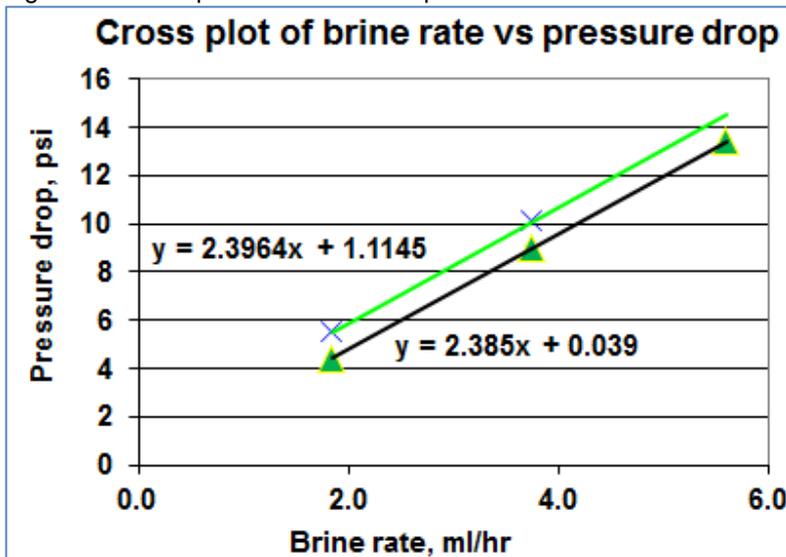


Figure 9: Reproducibility from different permeability modifying single slim tube runs.

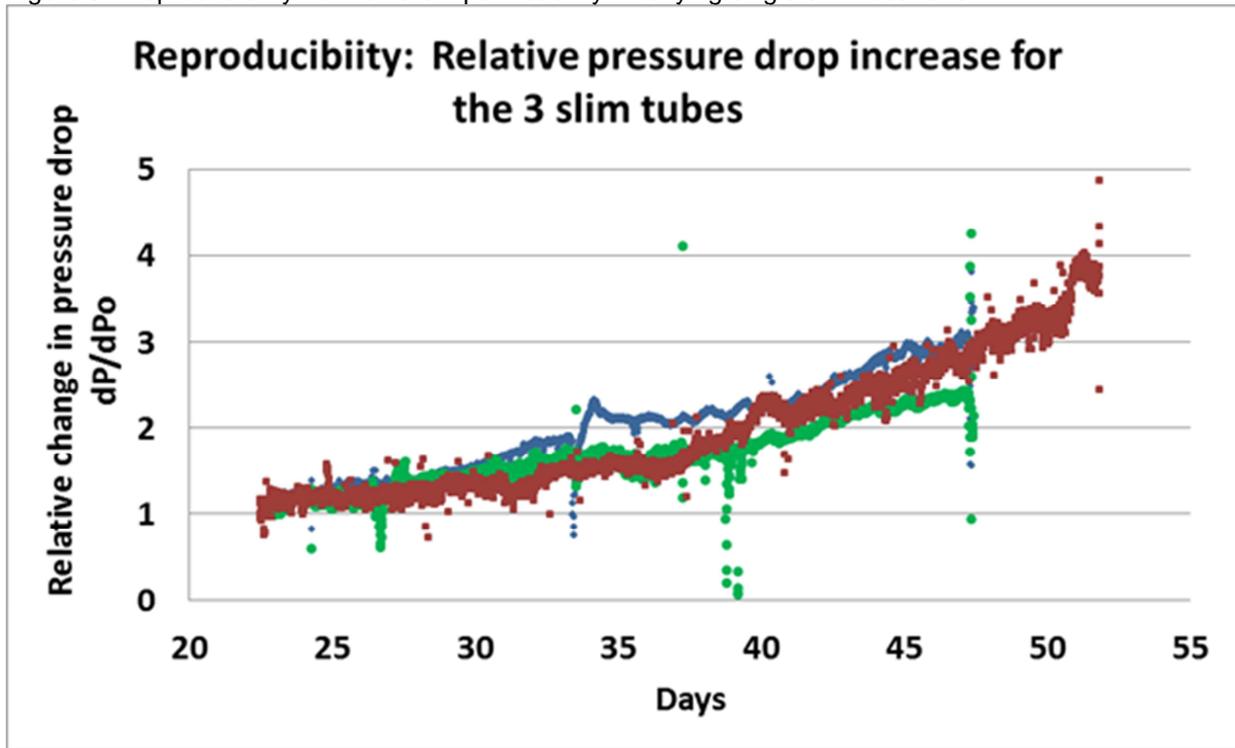


Figure 10: Set up for composite slim tube test.

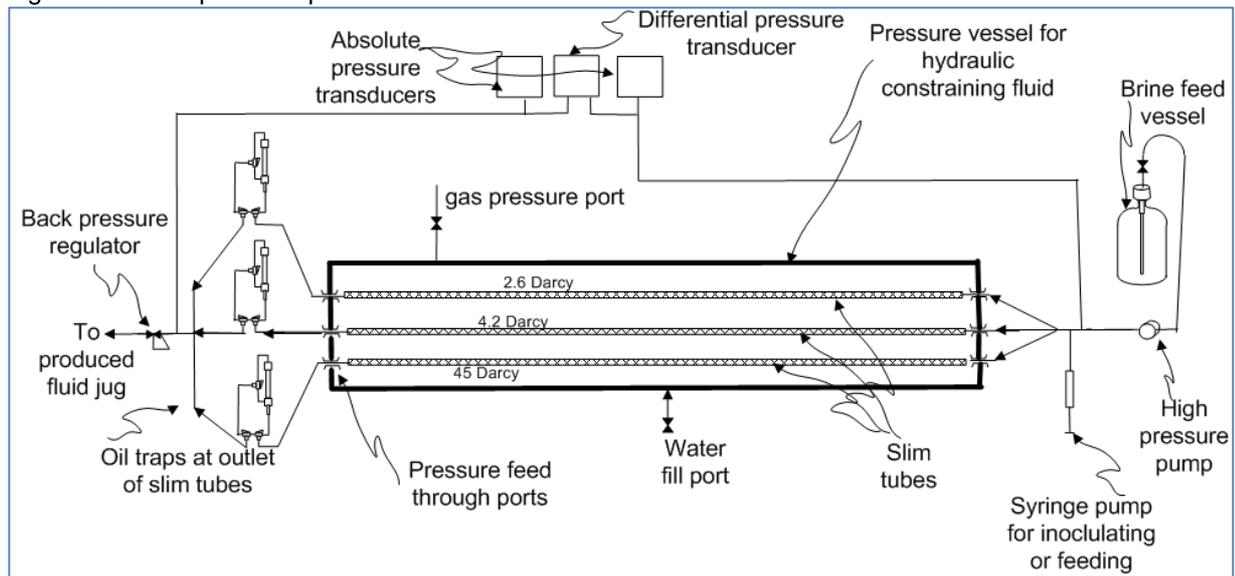


Figure 11: Permeability of slim tube A in the composite set up.

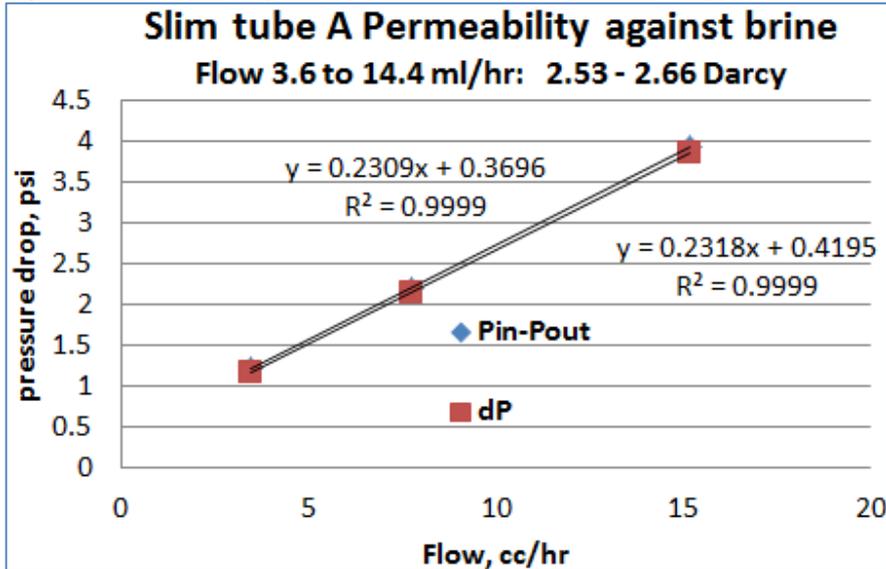


Figure 12: Oil recovery from each slim tube during the composite slim tube test.

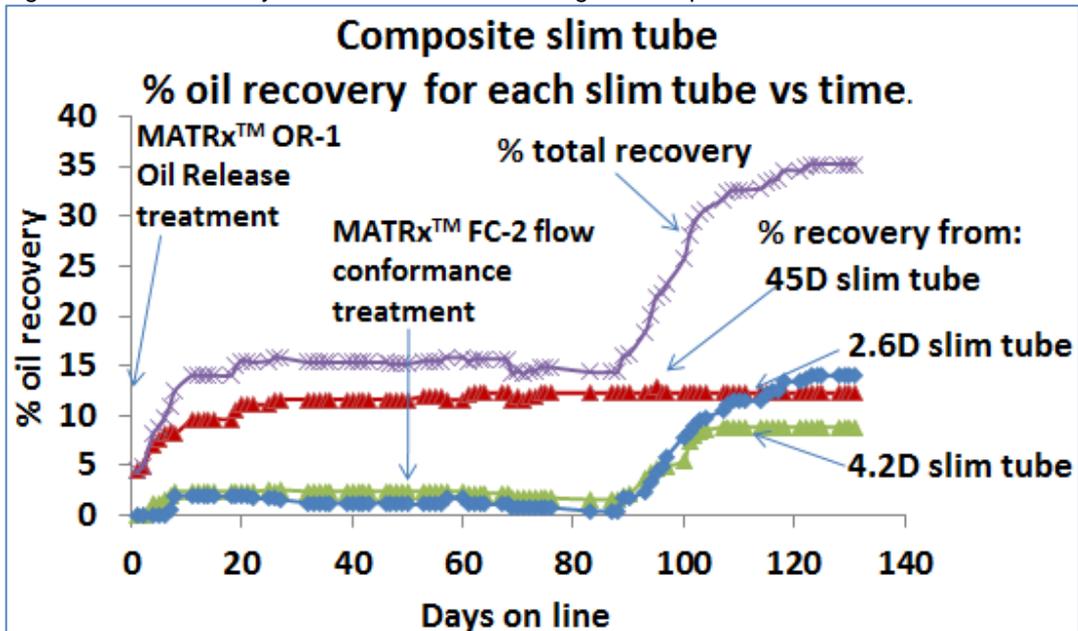


Figure 13: Pressure drop and overall oil recovery during the composite slim tube test.

