Treatment of High Viscosity Water Containing Back Produced CEOR Polymer

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Abstract

The global demand for oil and gas is continuing to rise, while each year more oil production fields become classified as mature. Nearly 2.0×10^{12} barrels (0.3×10^{12} m^3) of conventional oil and 5.0×10^{12} barrels (0.8×10^{12} m^3) of heavy oil will remain in reservoirs worldwide after conventional recovery methods have been exhausted [**1**] . This places additional importance on deployment of Chemical Enhanced Oil Recovery (CEOR), or tertiary recovery techniques to extract the remaining oil locked in the mature fields. Polymer flooding is the most commonly adopted CEOR production technique and requires the mixing of a water soluble polymer to the fluid being injected into a producing formation. The polymer functions as a thickening agent by increasing the viscosity of the injection water. This thick fluid results in a more effective sweep of the producing formation enabling additional recovery of oil not recoverable by water flooding alone (secondary recovery).

SNF Oil and Gas is the world's leading supplier of polymers used for CEOR production with first-hand knowledge and experience supporting producers in their transition to CEOR production methods. Many of these producers are operating in geographic regions that limit the amount of make-up water available for use in oil and gas production thus necessitating the recycle of produced water. CEOR produced water recycle places emphasis on water treatment because treated water quality can significantly impact the economics of a production facility. One of the hurdles that must be overcome when transitioning to a polymer flood CEOR process is the effect back-produced polymer has on the produced water treatment system.

SNF Oil and Gas and MYCELX Technologies completed a joint study to document the impact back-produced polymer has on the MYCELX RE-GEN produced water treatment systems. To accomplish this, the MYCELX system was evaluated on oil removal efficiency in the presence of various back-produced polymer concentrations or range of viscosities. As a result of this study the following points were verified:

1. MYCELX RE-GEN system performance is independent of the viscosity ranges tested (1 cP to 18 cP)
2. MYCELX RE-GEN system was able to achieve a greater than 95% removal on oil droplets 5 microns and larger
3. MYCELX RE-GEN does not remove the polymer from the back-produced water

INTRODUCTION

Global demand for hydrocarbons is continuing to rise each year. As fields mature, the oil production decreases with water production increases. The recovery factor of these fields currently average around 20% to 40% [**2**]. This equates to 60% to 80% of the Original Oil in Place (OOIP) locked in the reservoir.

It is typically more practical for operators to invest in enhanced recovery techniques than to develop a new field. In secondary recovery processes, the produced water is reinjected into the formation to maintain reservoir pressure to enhance the recovery of additional oil.

Many of the advanced or tertiary production techniques used by producers are referred to as Chemical Enhanced Oil Recovery (CEOR). CEOR production techniques are classified and characterized by the chemical alteration of the water injected into the producing formation to enable additional recovery of oil over and above the output achievable with conventional extraction methods. The deployment of these techniques can enable producers to recover an additional 10% to 35% OOIP. Abidin reports that 60-80% of oil is left in the reservoir following primary recovery production methods and because of poor sweep efficiency, 50 to 70% of oil remains in place following water flood or secondary recovery [**3**]. Cairn India has reported increased production from CEOR activities in the Mangala field in the Barmer basin. Following a successful polymer flood campaign, Cairn piloted an ASP flood suggesting incremental recovery on the order of 20% STOIIP (Stock Tank Original Oil in Place) after ASP chemical injection [**4**]. The more commonly deployed CEOR production methods are:

- Polymer Flood
- Surfactant Polymer Flood (S-P Flood)
- Alkali Surfactant Polymer Flood (ASP Flood)

A combination of both subsurface (reservoir characteristics) and surface considerations (geographic location, government/ environmental regulations and make up water sources) factor into the selection of which CEOR process is deployed. Water availability, cost and regulations are all careful considerations leading producers to adopt produced water management methods.

Reliable water treatment is critical to a facility that is utilizing a produced water recycle loop for a CEOR process. Poor water quality will increase the quantity of chemicals required to achieve the desired production gains associated with polymer flooding. This is a challenge because the presence of back-produced or returning polymer in the produced water can greatly impact the performance of existing produced water treatment systems. The potential increase of polymer required to mix into the fluid coupled with increasing returns of polymer can result in escalating costs.

In an effort to find a simple and robust produced water treatment process for produced water containing back-produced polymer, SNF Oil and Gas elected to complete a joint study with MYCELX Technologies Corporation. The objective of the study is to evaluate the impact higher viscosity back-produced waters have on the MYCELX RE-GEN water treatment system's ability to remove oil and suspended solids.

The removal of oil and suspended solids are critical to the efficient operation of a polymer flood production facility with a produced water recycle loop. Suspended solids and oil carryover in produced water used to prepare polymer solutions have the potential to impair injection to due blocking of reservoir pore throats. Impaired injectivity reduces the reservoir processing of the polymer solution, which can lead to lower oil production. Maintaining injection targets is fundamental to a project's success, and steps must be taken to ensure desired injectivity is sustained.

The study was completed with the oversight of both SNF Oil and Gas and MYCELX Technologies personnel present with the results reported below:

1. MYCELX RE-GEN system performance in oil removal is independent of the viscosity ranges tested (1 cP to 18 cP)
2. MYCELX RE-GEN system was able to achieve a greater than 95% removal on oil droplets 5 microns and larger
3. The MYCELX System does not remove the polymer in the back-produced water

This paper reviews the testing completed between MYCELX Technologies and SNF Oil & Gas. The data provided allows for the discussion of the implications and advantages associated with water treatment systems that do not require a polymer degradation step and there by enable the recovery of back produced polymer.

Water Treatment Challenges

CEOR production presents a number of water treatment challenges associated with back produced polymers. This stems from back produced fluid having elevated viscosities and tighter emulsions. Some of the more commonly deployed produced water systems operate on the principle of gravity or assisted gravity separation such as skim tanks, gun barrel tanks, induced gas flotation (IGF), and hydrocyclones. These systems are fundamentally reliant on the principles of Stokes Law which relates the density difference between an oil droplet (positively buoyant) or a solid particle (negatively buoyant) and a carrier fluid as related to the settling velocity of each component. The settling velocity is a key determinant for sizing separation equipment for a given effectiveness. Back-produced water from CEOR activities will be more viscous than produced water associated with primary and secondary production techniques. Stokes law illustrates that viscous fluid reduces the settling velocity of both positively and negatively buoyant particles. Systems utilizing this mechanism for removal of oil and suspended solids will be sized larger to account for the viscosity increases associated with CEOR production. Flotation systems are adversely affected by increased viscosity as viscous CEOR polymers tend to cause jetting of bubbles causing turbulence within the water which forms an uneven distribution of bubbles and inefficient removal of the positively buoyant particles [**5**]. Hydrocyclones are also sensitive to viscosity differences and given the potential for influent variability have not performed well in these applications.

While equipment sizing can be used to account for settling velocity, the viscosity increase attributed by the use of CEOR chemicals also promotes the stabilization of tighter oil in water dispersions than what might be expected in traditional produced waters [**5**]. As the oil droplet distribution moves to a smaller mean, removal requirements can shift be outside the treatment range of traditional separation equipment. Smaller droplet size and increased fluid viscosity can amplify settling times outside a practical range of traditional treatment equipment.

Given the difficulties treating back-produced water, one of industry's responses has been to dispose of the fluid. However, there are a number of fields limited by water availability and other areas impose restrictions through government regulations on the volume of make-up water allotted, or disposal regulations for offshore production. In these scenarios, facilities are forced to address the water treatment challenges associated with polymer flood produced water in a water recycle loop.

One technique using conventional water treatment equipment is to negate the effect of the injected water soluble polymers by destroying or degrading the returned polymer before treatment. Polymer degradation techniques reduce the fluid viscosity and limit the negative impact of elevated viscosity on the traditional produced water treatment systems mentioned above. As the polymer is susceptible to both mechanical and chemical degradation techniques, the polymer backbone can be cleaved, reducing the molecular weight of the polymer thereby reducing viscosity. While these methods have proven effective at reducing viscosity they also represent added costs through increased engineering and design complexity.

Mechanical degradation occurs when the CEOR polymer encounters the force of a high shear pump or high pressure choke valve [**6**]. The same forces used to break the polymer down are also imparted to any remaining oil present in the produced water. This can create tighter oil in water dispersions through a reduction in the droplet size of the oil remaining in the water phase. The mechanical degradation of the polymer is not always 100% effective since the shearing rate required can be impacted by a number of process parameters such as pressure drop, viscosity/ polymer concentration, and flow rate.

The most commonly used CEOR polymer can also be degraded through the addition of an oxidizer. Oxidizers generate free radicals that react with and cleave the backbone chain of the polymers resulting in a decrease of the molecular weight and viscosity drop [**6**]. In facilities recycling the treated produced water, any residual oxidizer carry over will degrade fresh polymer added for re-injection. This further complicates the process and requires the residual oxidizer to be neutralized before re-introduction of fresh polymer. Chemical oxidation is highly effective at reducing the viscosity but requires additional process equipment and process control to be successfully deployed. The varying viscosity levels/polymer concentrations change the quantity of oxidizer required to achieve the desired viscosity reduction which further complicates the chemical degradation step.

BACKGROUND

MYCELX RE-GEN is a deep-bed, granular media-based filtration system in which the media is surface functionalized by the MYCELX patented oleophillic polymer. The system is designed to back wash and regenerate the media and is deployed to remove suspended solids and dispersed and emulsified oil droplets from water. Performance is correlated to particle and droplet size distributions and demonstrated to be 95% efficient on droplets and particles 5 µm and larger. The RE-GEN is unique from typical physical separation-based processes in that it removes oil based on targeted surface affinity properties. The high surface area of the media enables RE-GEN to consistently contact and remove suspended solids and oil droplets 5 microns and larger.

This method of removal is reliant on surface contact of an oil droplet indicating that viscosity changes in the produced fluid do not affect MYCELX RE-GEN performance. This important property differentiates the RE-GEN from other traditional treatment methodologies in that it can eliminate a polymer degradation step thus providing producers a cost effective way to recycle back-produced polymer water. Furthermore it enables tertiary recovery of oil in regions where disposal and source water options are limited.

The SNF CEOR water soluble polymer is not captured by the RE-GEN media during water treatment. This is because RE-GEN's mechanism of oil removal is reliant on surface to oil droplet contact. This enables producers to recover the back-produced polymer thereby reducing the volume of fresh polymer required to achieve the desired injection viscosity. Back-produced polymer contains a wide distribution of polymer chain lengths due to the forces subjected to it on the path through the oil bearing formation. Recovery of the varying polymer chain lengths may prove beneficial to the operator as wide molecular weight distributions of polymer could provide more effective at penetration into varied pore sizes encountered in some formations. Additional research need to be completed to determine if this would propagate the sweep effect of the polymer flood further into the formation allowing for increased production over a tight distribution of polymer molecular weight.

Test Set-Up

In order to test the effect of changing polymer concentration or viscosity on the RE-GEN technology a controlled test set-up was developed. The test setup allows for single variable manipulation while gathering multiple data channels on the effects. The test setup utilized is shown in Figure 3.

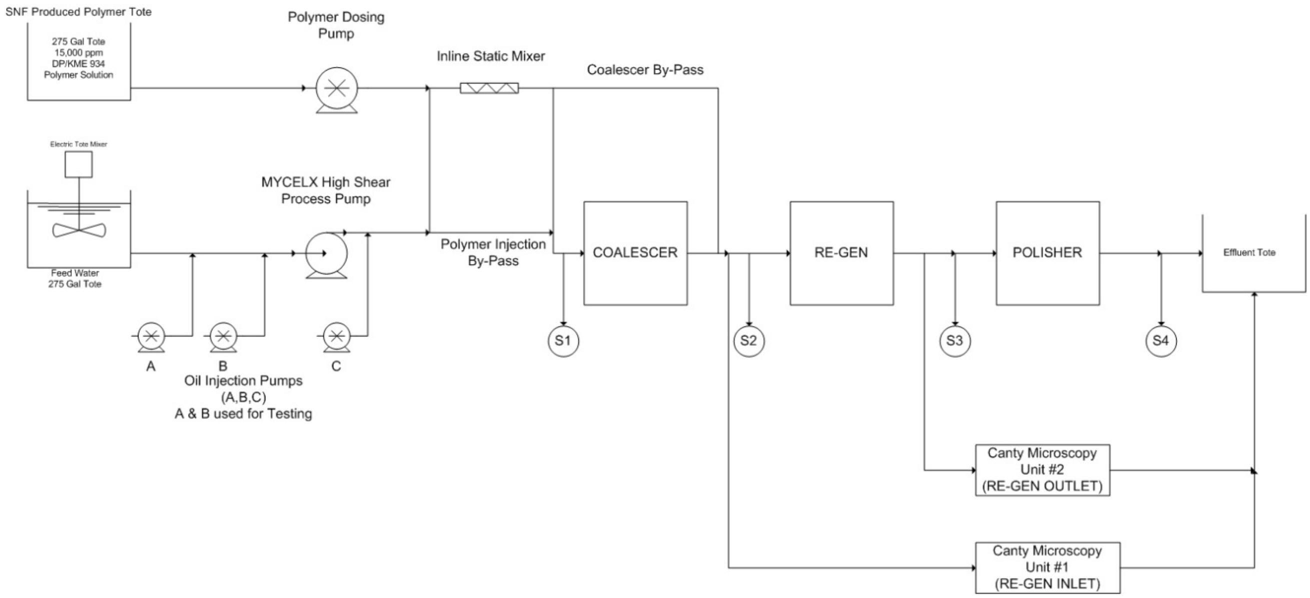

Figure 1: Process Flow Diagram MYCELX Test Set Up for SNF Testing

The test setup utilizes batch mixing for addition of suspended solids (ISO test dust standard). Oil contamination is controlled in the loop by two positive displacement metering pumps. Shear that affects droplet size is controlled through a deep well jet pump at 3,600 rpm with variable backpressure. Polymer mother-solution is added through the metering pump skid with static mixer. This set-up allows for process control and enables variability of oil, solids and polymer dosing rates for evaluation of the system under a range of loading conditions. The setup also contains continuous online oil content monitors (microscopy) and hand held oil in water analyzers which utilize fluorescence as well as infrared technologies. Third party labs were utilized to verify and validate onsite analytical data.

ANALYTICAL TECHNIQUES

The analytical tests performed are listed below. *Test America* was the third party lab selected to validate the onsite analyses for oil and grease.

- Polymer Concentration – SNF Laboratory, Riceboro, GA – Residual Polymer Test
- Oil in Water Concentration 3rd Party Lab – EPA 1664
- Oil in Water Concentration (Onsite) – Handheld Flourometer
- Viscosity (Onsite) – Brookefield Viscometer
- Microscopy (Onsite) – Online Microscopy Unit(s)

RESULTS AND DISCUSSION OVERVIEW

The MYCELX system was tested over a range of process conditions. Two parameters were varied to evaluate the MYCELX system response to process variances:

1. **Viscosity** (Polymer Concentration) – vary the dosing rate of the polymer solution in order to understand the MYCELX system's response to changes in viscosity
2. **Oil Concentration** – Vary the volume of crude oil dispersed into the simulated produced water stream

The study was completed in a series of 8 tests.

Tests 1 – 4 were conducted to understand the MYCELX system's response to high viscosity levels (> 7 cP) associated with polymer flood production

Tests 5 – 8 were conducted at lower viscosity levels to understand if the MYCELX system's performance would deviate from the observations made during Tests 1 – 4

Results and Discussion: High Viscosity Testing (> 7 cP)

Tests 1-4 were conducted to understand how high viscosity conditions influence the MYCELX system's ability to remove oil. In the below discussion, the RE-GEN efficiency is highlighted as the results show the RE-GEN was able to remove 95% of oil droplets 5 microns and larger. This indicates that the elevated viscosities ranging from 7 cP to 18 cP had minimal impact on RE-GEN performance.

Handheld Flourometer – Oil and Grease Concentration

	AVG Viscosity (Cp)	AVG OiW INLET (ppm)	AVERAGE RE-GEN OUTLET OiW (ppm)	AVERAGE RE-GEN EFFICIENCY
Test 1	9.3	724.0	67.1	90.7%
Test 2	7.7	864.1	22.3	97.4%
Test 3	17.8	864.6	12.9	98.5%
Test 4	11.0	951.1	18.6	98.0%

Table 1: Averaged Flourometer results for Test 1 through Test 4

During the high viscosity phase of testing the viscosities were varied from 7 cP to a maximum of 18 cP as noted above. The RE-GEN efficiencies varied from 90.7% during Test 1 to a maximum of 98.5% during Test 3. Several Outlet Oil and Grease samples in Test 1 resulted in significantly higher data points (over 100 ppm O&G). This could be attributed to sampling error or improperly cleaned glass ware as a number of the analytical instruments were cleaned and re-used from previously tests.

Microscopy – Oil Droplet Size Distribution + Oil and Grease Concentration

Video microscopy units were used as an additional method of analysis to monitor OiW concentration onsite. Microscopy was used to produce oil droplet size distributions and provide a secondary measurement for OiW concentration. The averaged values generated by the microscopy unit are shown below.

	OiW Inlet (ppm)	OiW RE-GEN Outlet (ppm)	Inlet Droplet Size (Dn 90)	RE-GEN Outlet Droplet Size (Dn 90)	AVERAGE RE-GEN EFFICIENCY
Test 1	1,079.4	40.3	7.15	4.3	96.3%
Test 2	1,066.8	22.0	13.6	4.18	97.9%
Test 3	1,091.9	15.8	12.1	4.27	98.5%
Test 4	1,377.4	17.3	11.0	4.04	98.7%

Table 2: All values are an average of 48 cycles which consist of over 200 images per cycle

The inlet OiW data generated by the online microscopy units closely match the known volumetric injection rates of the oil dosing pumps. The inlet Oil in Water concentration ranged from 1000 ppm to 1300 ppm. The oil dosing pumps (solenoid metering type) were set to maintain a dosing of approximately 1200 ppm OiW.

The oil droplet size analysis generated indicates 90% of all oil droplets (Dn 90) entering the MYCELX RE-GEN system were 7 to 13 microns in size and below. The Dn 90 for the oil droplets leaving the RE-GEN was reduced to between 4.3 micron and 4.0 micron. The effluent of the REGEN system reduced the OiW concentration to a range of 15 ppm to 40 ppm and produced efficiencies of 96% or greater. The images shown below were taken from Test 3 where the observed viscosities were approximately 17 to 18 cP.

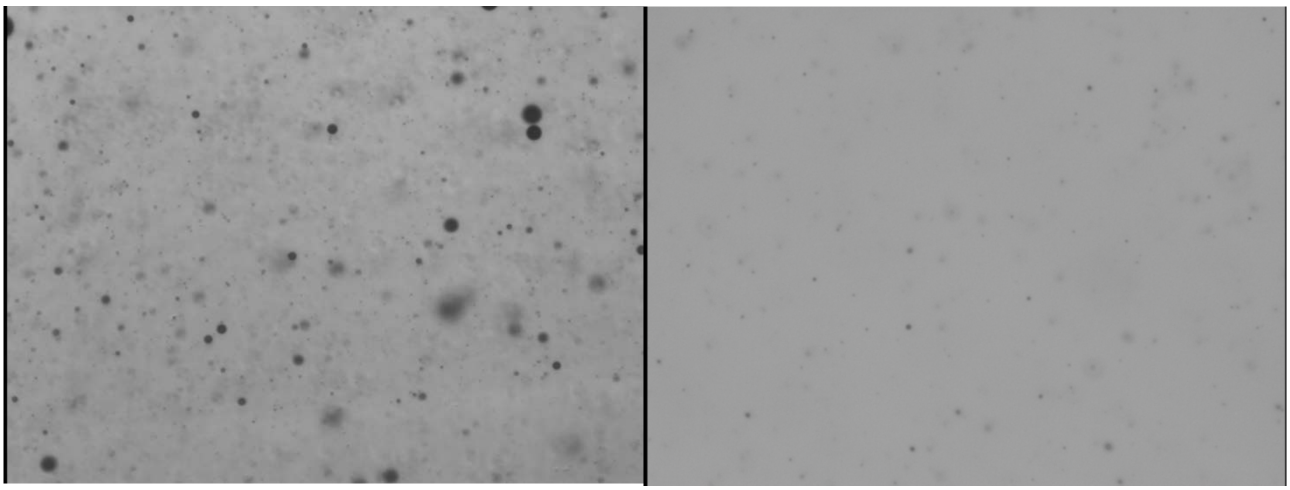

Figure 2: Microscopy Images taken from Test 3. RE-GEN Inlet Left - RE-GEN Outlet Right

Third Party Oil and Grease Concentration

	AVG INLET (mg/L)	AVERAGE RE-GEN OUT (mg/L)	AVERAGE REGEN EFFICIENCY
Test 1	272.5	14.1	94.8%
Test 2	402.5	8.0	98.0%
Test 3	154.0	3.6	97.6%
Test 4	285	13.3	95.3%

Table 3: Averaged Third Party Oil and Grease analysis

The third party analytical laboratory used EPA 1664 (Gravimetric Hexane Extraction for Oil and Grease). The EPA 1664 results were lower due to inherent differences in the methodology as compared to the onsite handheld flourometer and the microscopy analytical measurement devices. All three methods confirmed performance with average efficiencies varying from 94.8% to an upwards of 98.0%.

The large difference in the magnitude of oil is due to the extraction efficiency of hexane on this oil type. Typically other solvents are used in site-specific testing, due to the low extraction of asphaltenes and naphthenates.

Figure 3: Third Party Samples left to right: RE-GEN INLET and RE-GEN OUTLET

Results and Discussion: Low Viscosity Testing (< 5 cP)

The next phase of testing was to complete a series of low viscosity tests to understand if the trends observed in the high viscosity portion of testing continue. The viscosity levels evaluated were 2 cP – 4 cP. The data collected during Test 5 through Test 8 showed similar trends to those recorded for the high viscosity phase of testing.

Handheld Flourometer – Oil and Grease Concentration

	AVG Viscosity (cP)	AVG INLET (ppm)	AVERAGE RE-GEN OUT (ppm)	AVERAGE RE-GEN EFFICIENCY
Test 5	3.3	1,040.5	94.1	90.9%
Test 6	3.0	275.2	12.6	95.4%
Test 7	3.3	295.1	14.6	95.1%
Test 8	3.3	1,033.8	96.4	90.7%

Table 4: Average Flourometer results for flow viscosity tests.

Tests 5 and 8 were completed under high oil loading conditions. The average outlet of the MYCELX REGEN system for Tests 5 and 8 through Flourometer analysis was 94 and 96 ppm. This resulted in calculated efficiency values of ~ 91 %. This efficiency is lower than what was noted during the high viscosity/high oil tests made during the first phase of testing. During the low oil loading conditions (Tests 6 and 7) the outlet values were reduced to 12.6 and 14.6 resulting in a 95% efficiency for both tests.

Microscopy – Oil Droplet Size Distribution + Oil and Grease Concentration

The microscopy unit continuously monitored the inlet and outlet of the MYCELX RE-GEN system. The averages of the data recorded are in Table 6.

	OiW Inlet (ppm)	OiW Outlet (ppm)	Inlet Droplet Size (Dn 90)	Outlet Droplet Size (Dn 90)	AVERAGE RE-GEN EFFICIENCY
Test 5	1,199.3	44.4	11.14	4.6	96.3%
Test 6	438.4	7.9	11.15	4.9	98.2%
Test 7	465.6	10.9	8.8	4.9	97.7%
Test 8	1,096.9	49	7.8	4.6	95.5%

Table 5: All values are an average of 48 cycles which consist of over 200 images per cycle

The data generated by the unit shows a similar trend when compared to the data recorded in the high viscosity portion of the testing. The inlet OiW values closely mimic the volumetric injection rates of oil for each test. Test 5 and Test 8 had an oil injection rate of ~1200 ppm of oil. Test 6 and Test 7 had a volumetric oil injection rate of oil of 600 ppm. The efficiency of the RE-GEN system was consistently between 95% and 98% with average inlet Dn 90 values of 7.8 micron to 11.2 micron.

The reduction in oil droplet size through the RE-GEN system further supports the claim that single pass efficiency is controlled by oil droplet size distribution. The RE-GEN system performed as expected, effectively removing greater than 95% of all oil droplets larger than 5 um in diameter.

Third Party Oil and Grease Concentration

The averaged third party oil and grease samples collected for the low viscosity testing are shown in Table 6 below. EPA Method 1664 is a hexane extraction, evaporation, weight based method that does not quantify hydrocarbons in the same way as the handheld flourometer and microscopy methods. All the OiW concentrations generated by the third party Oil and Grease analysis were significantly lower than the known volumetric injection rate of oil, handheld flourometer, and microscopy analytical data.

	AVG INLET (mg/L)	AVERAGE RE-GEN OUT (mg/L)	AVERAGE REGEN EFFICIENCY
Test 5	291	9.8	96.6%
Test 6	107	2.5	97.7%
Test 7	39.1	1.8	95.5%
Test 8	129	2.5	98.1%

Table 6: Third party Oil and Grease averaged values

RE-GEN efficiencies generated by the third party oil and grease analysis closely compare to the efficiency results generated by the analysis completed onsite (Table 8).

	RE-GEN EFFICIENCIES		
Tests	3rd party	FLOURMETER	MICRSCOPY
Test 1	94.8%	90.7%	96.3%
Test 2	98.0%	97.4%	97.9%
Test 3	97.6%	98.5%	98.6%
Test 4	95.4%	98.0%	98.7%
Test 5	96.6%	91.0%	96.3%
Test 6	97.7%	95.4%	98.2%
Test 7	95.5%	95.1%	97.7%
Test 8	98.1%	90.7%	95.5%

Table 7: Averaged efficiencies for all analysis and all Tests (1 through 8)

The similarities in the RE-GEN efficiencies indicate that the lower recovery of hydrocarbons shown in the extraction efficiency of the EPA 1664 (3rd Party Lab) is linear for both the inlet and outlet of the REGEN. The third party data can be correlated to onsite measurements and used as an indicator of performance.

Results and Discussion: Polymer Analysis

Three inlet and three outlet viscosity readings were recorded for each test run. The results are shown below in Figure 5.

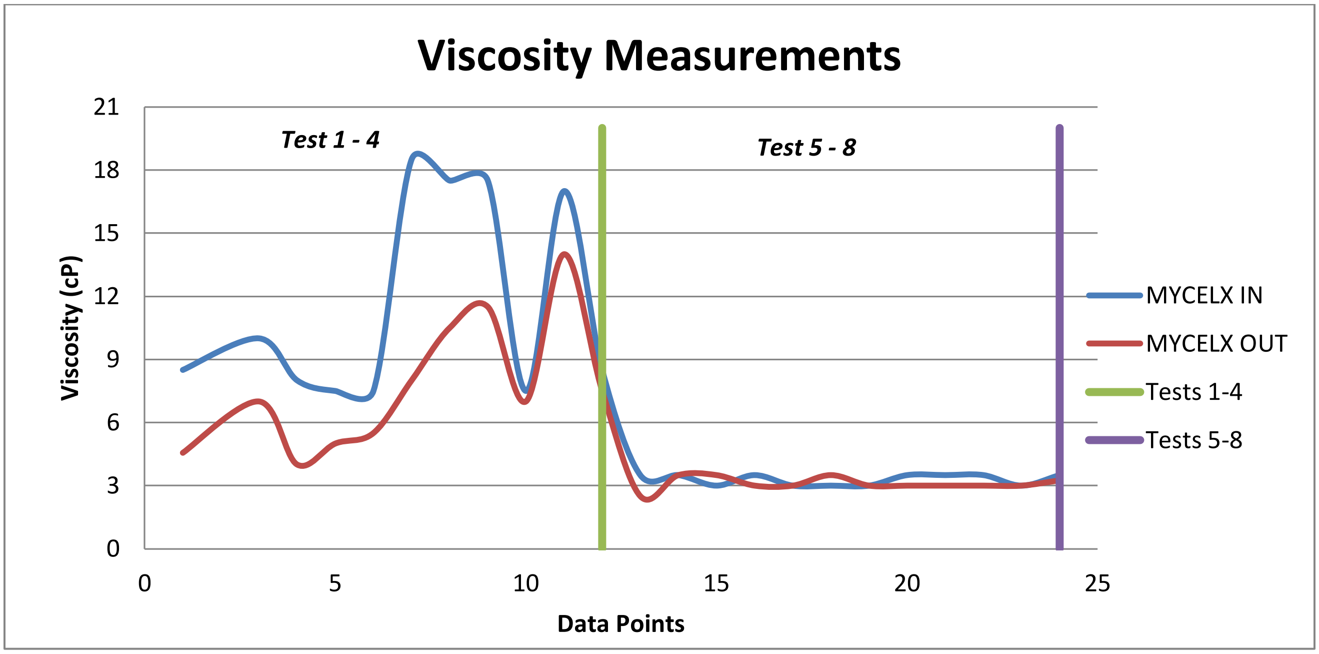

Figure 5: Brookfield Viscosity Measurements

During the high viscosity tests, differences between the inlet and outlet viscosity readings were noted. The differences ranged from a minimum of 0.5 cP to a maximum of 9.5 cP. However the lower viscosity tests resulted in a maximum difference of 0.5 cP between the inlet and outlet of the test system.

Residual polymer analysis was completed by SNF at the Riceboro, Georgia laboratory for samples from Test 7 and 8. The results are shown in the Table 9 below.

	System Inlet Polymer Conc. (ppm)	System Outlet Polymer Conc. (ppm)
Test 7	231	232
Test 8	310	308

Table 8: SNF Residual Polymer Analysis Test 7 and 8.

The residual polymer analysis showed no change in polymer concentration from inlet to the outlet of the MYCELX system. **The residual polymer analysis coupled with the viscosity readings indicated the polymer is not removed by the MYCELX system.** The variances between the inlet and outlet viscosities of the system can most likely be attributed to the shearing encountered by the test fluid through the piping, flow control, valves, process pumps, and pressure drops observed through the system.

Results and Discussion: Cumulative

Analysis of the data indicated that there is no discernable correlation between RE-GEN performance and the viscosity levels evaluated during the test (3 cP to 18 cP). This is further supported in the graph below.

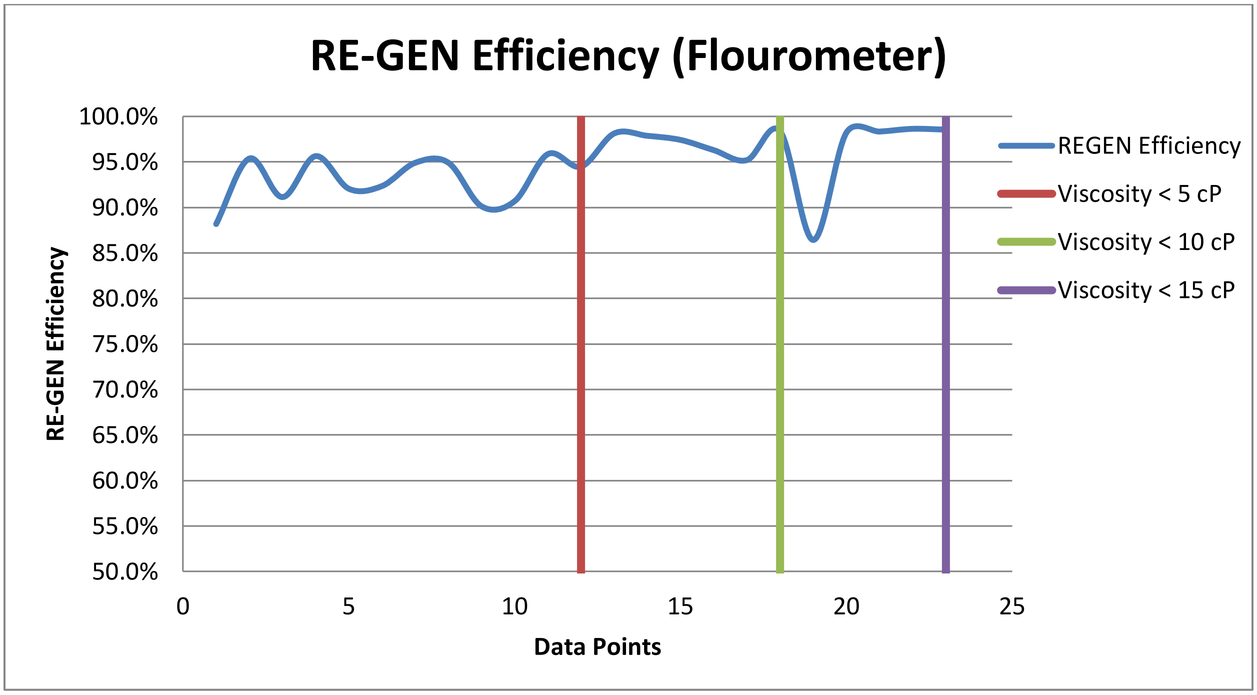

Figure 4: Efficiency of the MYCELX RE-GEN system with varying viscosity

The graph above depicts the REGEN efficiency defined by the flourmeter analytical equipment onsite. The vertical bars on the graph separate the viscosity ranges tested and present the RE-GEN efficiency curve between the various viscosity ratings.

As predicted, the RE-GEN efficiency is a function of the oil droplet size distribution and viscosity has no discernable impact on this relationship. Analysis of the REGEN efficiency data revealed a relationship between oil droplet size distribution (recorded as Dn 90) and RE-GEN efficiency shown in Figure 5 below.

Dn 90 was selected to describe the oil droplet size distribution as this represents 90% of the population of all oil droplets, thus providing an effective measurement for the oil in water dispersion created by the high shear pump used for testing.

- D = diameter of a given particle
- n = the population of oil droplets captured by the microscopy unit
- 90 = accounts for 90th percentile of all oil droplets

For example: When provided with a Dn 90 of 10 micron. This indicates that 90% of the total population of oil droplets are 10 microns in size or smaller, thereby describing how tightly dispersed an oil in water sample may be.

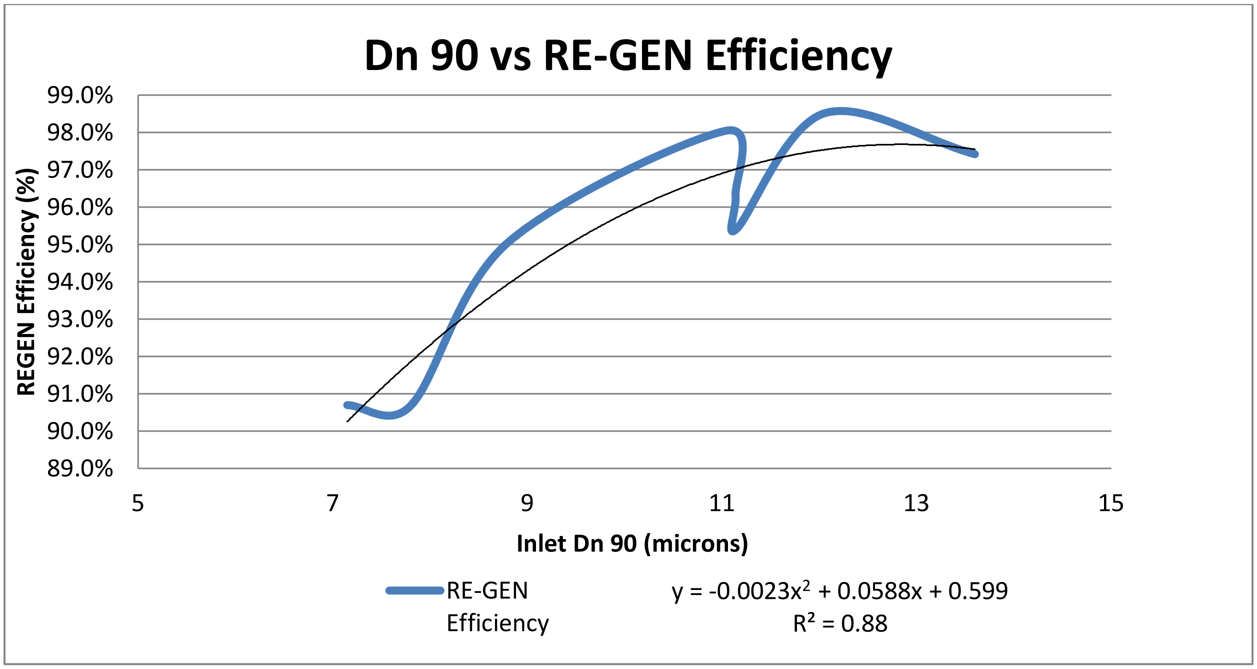

Figure 5: REGEN Efficiency as a function of Droplet size distribution (Dn 90).

The graph above relates RE-GEN efficiency as a function of droplet size distribution (Dn 90). Using a polynomial function an equation can be used to predict RE-GEN efficiency for this specific oil type with an **R^2 value of .88.** Further tests are in order to validate this function particularly for larger oil droplet size distributions.

The average Dn 90 for all tests (Test 1 through Test 8) entering the REGEN system was 10.2 micron. When 10.2 micron is inserted into the above equation an efficiency value of 95.6% is predicted for the MYCELX RE-GEN system. The flourometer efficiency calculated by averaging all fluorescence values yields an actual overall RE-GEN efficiency of 95.1 %. See Table 10 below.

	Averaged Inlet Dn 90 (microns)	Fluorescence Averaged RE-GEN Efficiency (Actual)	Fluorescence Averaged RE-GEN Efficiency (Predicted)
Tests (1 - 8)	10.2	95.1%	95.9%

Table 9: Observed RE-GEN Efficiency vs Calculated Efficiency

The average oil droplet sizes (Dn 90) of the RE-GEN effluent is shown in Table 11 below.

RE-GEN AVG Outlet Droplet Size – Dn 90 (microns)	
Test 1	4.3
Test 2	4.18
Test 3	4.27
Test 4	4.04
Test 5	4.6
Test 6	4.9
Test 7	4.85
Test 8	4.6

Table 10: Average REGEN Effluent Oil Droplet Size (Dn 90)

Over 90% of all oil droplets passing through the RE-GEN were below a maximum of 4.85 microns. T**his is further validation that the REGEN will remove 95% of oil droplets 5 microns or larger.** Based on **(Figure 3)** the previous statement is also valid for the viscosity ranges tested (2 cP to 18 cP).

Conclusion

The series of tests conducted confirm the oil removal efficiency of the RE-GEN system is independent of the viscosity of the simulated produced water stream. The data further supports the claims that efficiency is closely correlated with the droplet size distribution of the oil present and is not affected by variations in viscosity. It also correlates with the data collected from MYCELX's previous CEOR field pilots and installations.

The RE-GEN treatment system is capable of 95% efficiency of oil removal on oil droplets of 5 microns and larger in the viscosity ranges tested 3 cP to 18 cP.

RE-GEN media properties

1. Unaffected by viscosity fluctuations in carrier fluid
2. Unaffected by concentration fluctuations in contaminant
3. Does not de-nature polymer solution to provide oil removal
4) Backwashable and regenerable
5. Effective oil recovery to customer without addition of any coagulant or chemicals

The MYCELX RE-GEN system produced an overall oil removal efficiency (cumulative for all tests) of 95.1% based on the flourescence. Both the microscopy analyzer and third party lab analyses produced overall efficiencies of 97.4% and 96.7 %, respectively due to REGEN's ability to reduce the average droplet size (Dn 90) from 10.2 micron to 4.5 micron.

The test results showcased the MYCELX RE-GEN's performance (95% or greater efficiency on > 5 micron oil droplets) on concentration ranges and fluid viscosities that are outside the recommended operating conditions of other comparable technologies. Coupling the results produced during this test with MYCELX's previous field experiences on CEOR produced waters, MYCELX RE-GEN performance is a step change process improvement when compared to conventional treatment methodologies. The RE-GEN system treats polymer flood produced water with high efficiency, eliminates the requirement for a polymer degradation step, and does not remove the polymer. RE-GEN enables producers to have operational flexibility through minimizing the impact wide fluctuations in viscosity and OiW concentrations have on a system while still providing protection for the polymer mixing facility and injection wells further downstream.

Acknowledgements:

The testing was run in collaboration with SNF Oil and Gas. The testing facility was set up and run by MYCELX Technologies Corporation under the advisement of SNF Oil and Gas. Inspection of the MYCELX facilities was completed by Matt Hopkins (Technical Manager – EOR) and Noah Ganes (Field Service Supervisor – EOR, Canada).

MYCELX would like to acknowledge the process engineering support of Naushad Amlani and Ryan O'Heron for assisting in test set up and analytical testing.

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