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Case Studies: Improved Performance of High Brine Friction Reducers in Fracturing Shale Reservoirs

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Abstract

The primary purpose of friction reducers (FR's) used in stimulating shale reservoirs is to overcome tubular friction pressure and establish high pumping rates. Slickwater (or water frac treatments where friction reducers are used as main source of reducing tubular pressure) fracturing has increased significantly with the advent of horizontal shale stimulation. Technologies, including multi-stage fracturing of horizontal wells have increased frac volume requirements per well. Recent restrictions limiting fresh water usage and environmental concerns of flowbacks have created challenges for operators to adopt mechanical and chemical water treatment means to remove impurities from flowbacks for reuse in slickwater fracturing. However, most treatments do not remove brines from the water requiring development of high brine tolerant friction reducer to maintain high performance.

This study presents experimental and case studies of various cationic and anionic FR's of the similar molecular weight in high brine flowbacks collected from two major shale plays. Finger print water analyses of shale reservoirs were used as brine source for evaluation. Dynamic friction loop flow apparatus was used to evaluate the rheological properties and formation damage of the FR where high brine waters are being used as the main source of slickwater fracs.

Field data collected for two case histories document the ability of the high brine tolerant friction reducers to perform at a level consistent with traditional products used in fresh water. This confirms the experimental flow data obtained from dynamic friction loop investigations. Results obtained from this study can be used to optimize slickwater frac treatments where flowbacks are the main source of frac water. Primary objectives include.

- Comparison studies of new high brine tolerant friction reducer with conventional FR's used in the oilfield.
- Experimental data illustrating the performance of newly developed FR's in high brine shale flowbacks. Cost advantage can be realized by using less polymer, while reducing fresh water and disposal of the flowbacks.(will be addressed at a later publication)
- Case studies of wells treated with the new friction reducers show performance in brines similar to these achieved with conventional FR's when used in fresh water.

Introduction

In the early stages of shale play development, tight low permeability shale reservoirs were subjected to variety of fracturing techniques and fluids to achieve commercial quantities of gas. In an attempt to maximize the reservoir contact and increase conductivity, variety of fluids such as crosslinked borate, zirconate, and linear guar gel were used. Wells treated with guar based linear gel, borate, or zirconate crosslinked fluids resulted poor cleanups and under par gas production. However, gas production and well cleanups improved significantly when low viscosity "slickwater frac" treatments were used. Today, the industry has adopted slickwater systems as the workhorse of stimulating shale reservoirs due to its cost, availability and ease of post frac well cleanups.

Shale gas development in fields such as the Horn River and Marcellus plays require large volume of water to frac. (Arthur et al., 2009). Horizontal shale fracturing techniques utilize multiple stages, sometimes exceeding 25 stages per well. In some examples total water requirements can exceed one million barrels per well. In areas like Pennsylvania and western Canada produced water from saline subterranean formations is often used as main source of frac water for slickwater frac. Produced

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water is highly saline and contains both mono and divalent salts which either need to be pre-treated or disposed. Both methods have some associated cost, but the pretreatment method normally cost less than disposal. In Pennsylvania where disposal wells are often not an option, recycling and re-using of produced water is the most economical alternative method of reducing operation cost and demands for fresh water. Most states and provinces have restrictions and limitations on fresh water use for fracturing or other industrial activities. Several recycling techniques are practiced to cleanup and reuse the flowback water; however, these techniques do not remove dissolved salts and hardness from the flowback water. In fact, examination of field recycled water in the Horn River and Marcellus fields show most water recycling programs gradually increase the observed brine content, in particular divalent brines, which are particularly problematic for most friction reducers.

This paper examines the performance of new high brine tolerant polymers in multivalent high brine waters. Samples of flowback and production waters from both the Horn River and Marcellus regions were analyzed and then used as a brine source for this investigation.

We were inspired to find and utilize several modified high molecular weight water internal based polyacrylamides as the new friction reducers to examine their performances under hostile high brine conditions. Field case studies validate the experimental results which are presented in this study. Test results show that the new high brine tolerant friction reducers significantly improve performance of slickwater fracturing when applied with high brine waters. Experimentally, several friction reducers were tested to evaluate their performance. This study was conducted mainly using a 60 liter (16 gallons) capacity friction loop through 3/8" 1/2" and 5/8" stainless steel pipes (Table 1 and Figure 1). Field and experimental results show the new friction reducers exhibit significant performance improvement when produced water is used in shale fracturing treatments.

There is limited availability of injection wells in western Canada and Appalachian Basin for disposal of production water. Additionally, the use of fresh water restrictions has created challenges and a need for reusing flowback water as the main water source for fracturing. Several water recycling techniques are used to recondition flowback waters to an acceptable level wherein iron, solids, and other impurities are removed. Dissolved salts and hardness cannot be removed unless flowback water is treated by expensive and costly distillation.

E&P companies are choosing to both use more produced water and recycle flowback water to reduce operational costs. Service companies working diligently to provide fracturing fluids which perform in high salinity conditions. One challenge addressed in this paper is selection of the proper friction reducer based on their performance. Standard commercially available friction reducers do not perform adequately in these high salinity waters. Economic constraints dictate that chemical loadings not increase when using high brine content water as the main source of the frac water. It was therefore necessary to redefine and develop a friction reducer that can perform well under high brine conditions without increasing its loading.

Environmental Implications

Recently public interest in the process of hydraulic fracturing has grown substantially, much in part to the change in the scope of fracturing treatments and the growth into geographic areas that were previously undeveloped by the oil and gas industry. To compound the issue, the media has highlighted fracturing treatments and has over emphasized the potential for environmental hazards, both real and perceived, associated with the practice. Potential environmental issues surrounding fracturing have included the potential for fresh water aquifer contamination, chemical spills at surface, and the additional burden on fresh water resources resulting from high volume slick water treatments (Arthur et al., 2009).

Fresh water usage for large scale slick water fracturing projects is also a very real and visible concern of the public. A typical slick water frac can use tens of thousands of barrels of fresh water for a single stage of a treatment. Although some of this water is recovered after the treatment, the recovered water is no longer fresh as it will dissolve substantial amounts of salts while in the formation. Recovery of this brine water presents even more challenges relating to disposal of these substantial volumes of non potable water (Arthur et al., 2009; Blauch 2010; Baycroft et al., 2005). North America is currently tracking dramatic declines in the reserves of fresh water, large in part to population growth and rising temperatures. It therefore has become critical to substantially reduce the amount of fresh water that is used for fracturing operations. Treating recovered brines after frac treatments or produced brines from existing subterranean reservoirs has been shown to not be cost effective. Since conventional fracturing chemicals have been shown to have hindered performance in the presence of brines, developing fracturing chemicals that will perform effectively in untreated brines is a necessary step to reduce the use of fresh water and at the same time resolve the problem associated with disposal of recovered brine.

The primary chemical component used for slick water fracturing is the friction reducer. Two new friction reducers were developed to perform well in high brine waters. For the Horn River project, the new friction reducer allowed the use of a produced brine rather than fresh water. The estimated fresh water savings from a single project is approximately forty million gallons (Parfitt, 2010).

Friction Reducers

A friction reducer for aqueous applications is typically a water soluble polymer. These polymers need to have substantial molecular weight are ideally linear and flexible. The aqueous phase may be defined by parameters such as: pH, alkalinity, total dissolved solids, total suspended solids, ionic strength, and specific cationic and anionic species. In addition, in mixed media phase's volume percent, weight percent of the non-aqueous phase need to be taken into account. Other properties which influence polymer solvent interaction are temperature, polymer concentration and fluid dynamics (Virk, 1975). The aqueous solvent allows the polymer to solubilize in accordance to thermodynamic, statistical thermodynamic and kinetic principals. If the solvent allows favorable dissolution and stability the polymer will provide maximal friction reduction. For aqueous phases minimal ionic strength is preferred for most water soluble polymers based on acrylamide. However this interaction depends on the specific polymer and aqueous phase being used. The polymer, homopolymer, copolymer or a terpolymer of an non-ionic, anionic, cationic or amphoteric disposition; when charge type is a variable the charge density is also a variable. Depending on the type of charge and the level of charge on the polymer the interaction with the aqueous phase will greatly depend on the dissolved ionic species and pH. Anionic polymers based on acrylic acid become less soluble as the pH falls below 4.5 and many cationic polymers can hydrolyze as the pH grows above 9. In addition acrylamide moieties in the backbone can also hydrolyze leading to an increased anionic nature. Polymers typically used as friction reducers do well in aqueous systems of low to moderate ionic strength where the ions are monovalent. In general problems occur when the levels of monovalent salts increase above 7% or where divalent and trivalent species are above 0.5%. In these cases the polymer should be modified in order to be effective friction reducers. This is accomplished by variation of the monomer type and ratio. Therefore the friction reducer's performance may be tailored to the specific aqueous phase used (Kaufman *et al.*, 2008).

The above scenario assumes the entire amount of polymer used as a friction reducer has been allowed to solvate. Typically these friction reducers are water internal emulsions in which the polymer resides in the water phase. In order for the polymer to be effective as a friction reducing additive, it must migrate from the internal emulsion into the aqueous stimulation fluid. This means the emulsion must be destabilized when it is introduced to the stimulation fluid. Ideally this destabilization process is rapid and complete. The factors that affect the polymer's dissolution may also have a minor to large influence on this destabilization process. Therefore the initial emulsion must be stable to a variety of storage conditions yet invert into the stimulation fluid when introduced. Therefore the surfactants used for the emulsion must be tailored to the properties of the aqueous phase.

The proposed mechanisms by which these friction reducers work are numerous; however, the effect is well documented and practiced. The hydraulic horsepower demand can be reduced up to 80% theoretically depending on the flow conditions (Virk, 1975). This reduction can provide a large cost reduction to the stimulation. As volumes of aqueous based stimulation fluids used per job increase (Parfitt, 2010) and horizontal multi-zone wells become a greater segment of producing wells, the need for effective friction reducers increases.

From the previous arguments in order for a friction reducer to be effective the polymer and the surfactant package need to be customized for the application. A polymer may work in a variety of brines but the surfactant package may be incorrect for the fluid. In that case not all of the polymer will be available to act as friction reducer. In addition the surfactant package may be ideal but the polymer will not hydrate properly. Therefore experience will guide the design of the polymer and the surfactant package and applications in the lab validate the performance and the field application will be the final confirmation.

The performance of a friction reducer is typically dependent on three parameters. First is the effectiveness of polymer in the fluids system. We found some polymers do not unfold rapidly in brine waters. The second, what percentage of the polymeric component is totally is released from the emulsion, and third, how fast the polymer inverts in brine condition. All of these factors in combination will determine the performance of the friction reducer in high brine fluids. Therefore design of friction reducers must consider the polymer and the surfactant package as a combination and attempt to maximize the potential of each facet or attempt to balance each to reach an acceptable economical result.

Experimental

Flow Loop Evaluations

Evaluation of the friction reducer performance was performed by using a re-circulating flow loop. Friction reduction was determined by flowing the water at a high rate successively through 3 different sizes of tubing: 5/8", 1/2", and 3/8". Differential pressure was recorded across a 10 ft section of tubing. Untreated water was used as a baseline and percentage friction reduction (%FR) was determined as shown in equation 1.

$$\text{Equation 1: } \%FR = (dP \text{ water} - dP \text{ FR treated water}) / dP \text{ water} \times 100\%$$

The flow loop consisted of a 60L (16 gallons) reservoir, a progressive cavity pump, a 7hp electric motor, a flow meter, and a data acquisition unit, as shown in Figure 1. A summary of the flow parameters of the apparatus is shown in Table 1. Ambient temperature water (fresh or brine) was pumped through the loop at a rate of 12 US Gal/min for 60 seconds to establish the baseline differential pressures. The friction reducer chemical was then added to the circulating water and the change in differential pressure was recorded over time. Typical friction reducing additives will result in a friction pressure reduction of 50 to 75% in field case studies. In most cases, the maximum performance of 70% friction reduction is achieved.

Water Salinity Impact

The ionic strength and the specific ionic species present in frac fluids have a large impact on the hydration performance of friction reducers (Aften, 2010). Normally, any given polymer, the friction reduction performance is directly dependent on the level of salt content in the frac fluid. As the level of salt increases, the performance of friction reducers decreases. Some friction reducers are more sensitive than others due to the polymeric structure, sequence of the polymerization, percent charge, and molecular distributions. Ionic strength depends on not only the weight percent of the salts but also the specific ionic charge of the salts. Most di and tri-valent salts increase the ionic strength at a greater level per mole than monovalent salts. Some friction reducers may when mixed with certain brine waters, may completely or partially precipitate exhibiting lower performance and may cause formation damage (Woodroof *et al.*, 1977).

Inversion Time

Inversion time of friction reducer is defined as the times required for the friction reducer to unfold achieving its full viscosity. To achieve maximum friction reduction, the polymer must reach its maximum inversion time by dissolving into the aqueous solution rapidly. Some of the friction reducers designed for fresh water applications invert very slowly in brine waters. Therefore, in scenarios where the only frac fluid in the location is the flowback water, the friction reducer will perform below expectations. In this case, operators have to increase the polymer loadings in order to achieve their target pumping rates. However, when the new friction reducer is used, it provides expected friction pressure reduction polymer loadings similar to conventional products. This phenomenon leads to a wider margin of pumping flexibility which may result higher pumping rates and more efficient proppant transport.

New Friction Reducer Development

We were inspired to take this challenge and address industry concerns by intensive research program leading to development of new polymers. This research was undertaken to identify a technical solution to the existing gap requiring a robust friction reducer that can perform in both benign and hostile environments. Selection criteria were to develop a friction reducer that can tolerate high salinity produced waters without increasing loadings yet exhibiting expected friction reduction characteristics. This work focused on evaluating a series of friction reducers using a dynamic pipe friction loop as the main tool of measuring their performance in fresh water, various produced brines, and flowback waters.

Top performing FR candidates were selected based on their performance and ease of handling.

Laboratory Methodology and Study

Four friction reducers were examined; Friction reducers B, C, and D were anionic, while friction reducer A was cationic. Friction reducers A and B were commercially available industry standard products. Friction reducers C and D were suspected to show higher brine tolerance. The friction reduction test was conducted as shown in the experimental section. The aqueous systems studied were standard fresh water, 7% NaCl, produced water used in Horn River Fracturing, postfrac simulated Marcellus formation flow back brine, and a standard API brine (2.5% CaCl₂, 8.5% NaCl). The ionic profiles of the Horn River and Marcellus brines used in the friction loop testing are presented in Tables 2 and 3.

Results

Laboratory Friction Reduction

Performance of all the friction reducers in fresh water was similar as Figure 2 illustrates, all instantly achieving a friction reduction of approximately 70-73%. The differentiation in performance in 7% NaCl is obvious, as shown in Figure 3, with friction reducer D performing best. Both friction reducers A and C are adversely affected when chloride levels and total ionic strength are increased, but not as significantly as when the same friction reducers were subjected to divalent cations such as calcium and magnesium, as illustrated in Figure 4, API Brine (2.5% CaCl₂, 8.5% NaCl) or Figure 6, Marcellus Flow Back Water. As shown in Figures 4 and 6 the friction reducer inversion rate and maximum total friction reduction was greatly lowered with all chemicals with the exception of friction reducer D. Of interest was the similar performance of friction reducers B, C, and D in the produced water used for Horn River fracturing as shown in Figure 5. Based on the water analysis, the key difference in water compositions was a lower percentage of divalent ions found in the Horn River water when compared to the API Brine and Marcellus water and possibly also the lower overall salt concentration.

Conventional anionic and cationic friction reducers (A and B) were found to be dramatically affected by either high concentrations of total dissolved salts or moderate concentrations of divalent cations. Friction reducer C originally suspected to offer brine tolerance showed improved performance in the presence of moderate concentrations of salts especially when compared to friction reducers A and B, however performance quickly dropped when salt concentrations were further elevated. Friction reducer D showed stable performance, almost always achieving greater than 70% friction reduction in all brines tested.

Case History #1

The first case history is of two horizontal wells drilled in the Montney shale gas formation in the foothills of North East British Columbia. These wells have vertical depths of approximately 6500' and are completed with a monobore of 4.5" 13.5# casing with an internal diameter of 3.92". The typical completion places 5-7 fractures in the horizontal using 3-4 perforation clusters of perforations spaced roughly 250' apart isolated by means of pumped down plugs. Each treatment consists of between 220 and 330 klbs of predominately 30/50 and 20/40 natural sand with a tail-in of curable resin coated proppant to both minimize proppant flow back and provide additional conductivity near the wellbore. Fluid volumes of between 3800 and 6300 bbl were typical for each interval, plus the additional fluid required to pump down the plugs. Although there is initially substantial friction in the perforation and near-wellbore region it is assumed that once the treatment is completed and flushed that these frictions can be assumed to be negligible. Making this assumption we can calculate the minimum effectiveness of each friction reducer. Both treatments used a friction reducer loading of 1.0gpt for their duration, consistent with the presented laboratory data.

In Figure 7 we can observe a treatment performed using fresh water and friction reducer "B". At the end of the treatment we can observe the final pumping rate (70.3 bpm) and pressure (8300 psi). Measuring the initial shut in pressure (ISIP) of 2840 psi and knowing the measured depth to the first perforation (10150') we can calculate a friction gradient of 0.54 psi/ft. When compared to a theoretical friction for fresh water of 1.55 psi/ft we can determine that the minimum friction reduction is 65%.

In Figure 8 we can observe a treatment performed with a mixture of Montney flow back water, fresh water and the salt tolerant friction reducer "C". After a previous well had been treated with a total of approximately 2 million gallons roughly 30% was flowed back and tested at 150,000 ppm total dissolved solids. A typical water analysis of the Montney formation flow back water is shown in Table 4. To this flow back fluid fresh water was added to make up the required additional volume in approximately a 3:1 ratio for the treatments on the following wells. At the end of the treatment we can observe the final pumping rate (69.7 bpm) and pressure (8430 psi). Measuring the ISIP of 3200 psi and knowing the measured depth to the first perforation of 9140' we can calculate a friction gradient of 0.57 psi/ft. When compared to a theoretical friction for fresh water of 1.53 psi/ft we can determine that the minimum friction reduction is 63%.

These two treatments confirm the laboratory data and show that the performance of the salt tolerant friction reducer in recycled water is nearly the same as the conventional friction reducer in fresh water.

Case History #2

The second case history is one stage of a multistage vertical well of tight gas formations in the foothills of North West Alberta. This well was cased with 4.5" 15.1# casing with an internal diameter of 3.826". A total of 5 fractures were completed in this well. The example treatment was placed into 4 perforation clusters perforated between 12100' and 12400'. The treatment consisted of 220k lbs of 40/70 pre-cured resin coated proppant transported with 3600 bbl of slick water treated with 1.0 gpt friction reducer. In this well the first stage was performed with fresh water and the subsequent treatments used a mixture of recycled frac water and fresh water with a blended salt content of ~10000 ppm total dissolved solids. Again the friction reducer performance was determined based on the pumping rate and pressure at the end of the treatment, however in this case the injection rate was decreased stepwise rapidly at the end of the treatment so it was necessary to perform the calculation prior to the end of the displacement. This required an adjustment of the pressure to account for the contribution to hydrostatic pressure of the proppant. Using the data at the 69 minute mark an adjustment of 190 psi was required.

In Figure 9 we can observe the example treatment with friction reducer "D". At the point near the end of the treatment (indicated by the arrow shown on the graph) we can observe the final pumping rate (59.0 bpm) and pressure (9870 psi). Measuring the initial shut in pressure (ISIP) of 5800 psi and knowing the measured depth to the first perforation (12100') as well as the 190 psi hydrostatic contribution we can calculate a friction gradient of 0.35 psi/ft. When compared to a theoretical friction for fresh water under the same conditions of 1.27 psi/ft we can determine that the minimum observed friction reduction is 72%.

Conclusions

1. High brine tolerant friction reducers provide significant benefit in reducing polymer loadings and the environmental footprint by using produced waters rather than fresh water.
2. Experimental results show the high brine tolerant friction reducers C and D can be used in produced Horn River brine without increasing polymer loading.
3. Brine tolerant friction reducer D can be used in water with higher levels of CaCl_2 when compared with other commercially available friction reducers.
4. The new friction reducer D exhibits lower friction pressure values, in brine waters, which may allow higher pumping rates resulting in more efficient proppant transport.
5. Case studies confirm the effectiveness of high brine tolerant friction reducers under field applications with produced and recycled water. This demonstrates that brines may be used for slickwater frac treatments, without compromising effectiveness.

Nomenclature

6. bbl = Barrel(s)
7. FR = Friction reduction (reducer)
8. g = Gram
9. Kg = Kilogram
10. L or l = Liters
11. L/m^3 = Liters per cubic meter
12. m^3 = Cubic meters
13. meq = Miliequivalents
14. $mmol$ = Millimoles
15. m^3/min = Cubic meters per minute
16. mD = MilliDarcy
17. MPa = MegaPascals
18. ppm = Parts per million
19. $^{\circ}C$ = Temperature in Centigrade
20. $^{\circ}F$ = Temperature in Fahrenheit
21. $\mu g/l^3$ = Micrograms per liter

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Table 1- Dynamic Friction Flow Loop Parameters

Pipe Size (inches)	Reynolds Number	Shear Rate (1/s)
5/8	76668	3880
1/2	88257	5919
3/8	124429	16586

Flow Rate: 12 Gal/min (45.4L/min), Tubing Length: 10ft

Table 2 Typical Horn River water analysis

Anions	Conc (mg/L)	Cations	Con (mg/L)
Chlorides	15,490	Sodium	11,200
Sulfate	0.0	Calcium	360
Bicarbonate	2,195	Magnesium	140
Carbonate	0.0	Barium	340

Table 3 Typical Marcellus water analysis

Anions	Conc (mg/L)	Cations	Con (mg/L)
Chlorides	47,480	Sodium	28,000
Sulfate	0.0	Calcium	1,100
Bicarbonate	0.0	Magnesium	960
Carbonate	0.0	Potassium	510

Table 4 Typical Montney water analysis

Anions	Conc (mg/L)	Cations	Con (mg/L)
Chlorides	109,434	Sodium	68,689
Sulfate	1.0	Calcium	898
Bicarbonate	894	Magnesium	126
Carbonate	0.0	Barium	1074

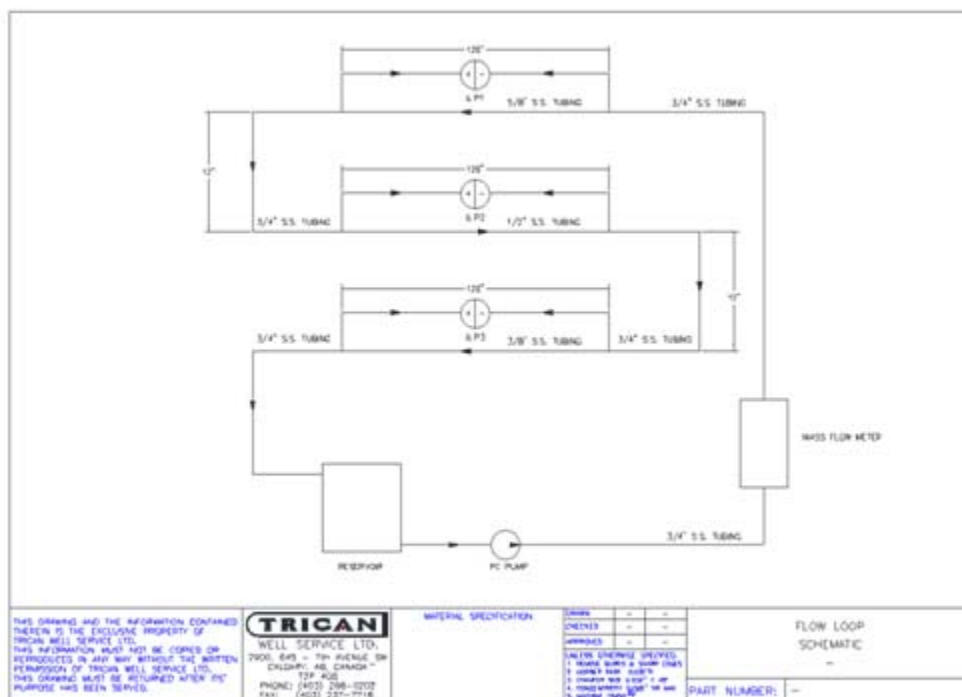


Figure 1-Schematics of the dynamic flow loop used for testing

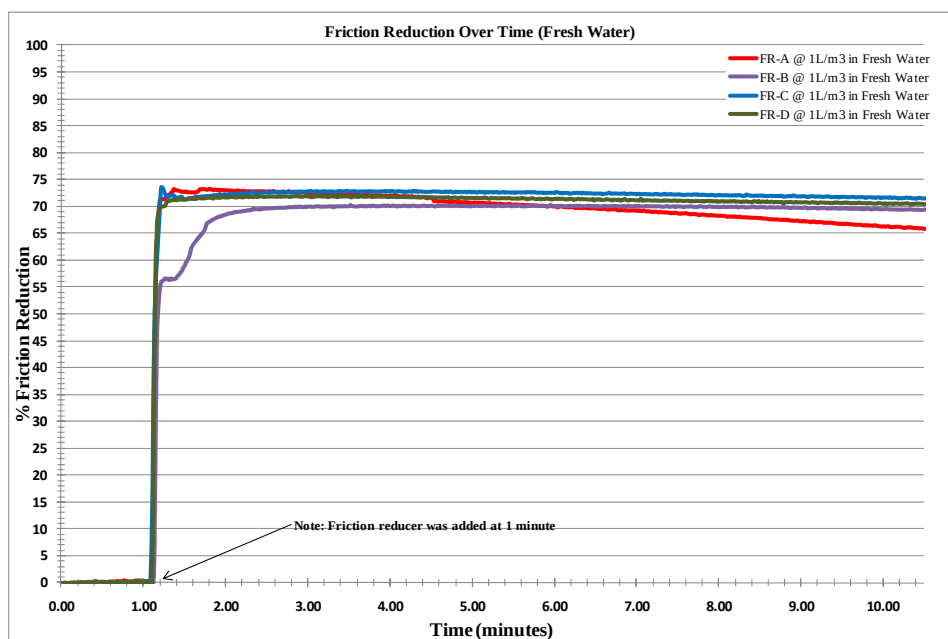


Figure 2 - Friction data of friction reducers in fresh water

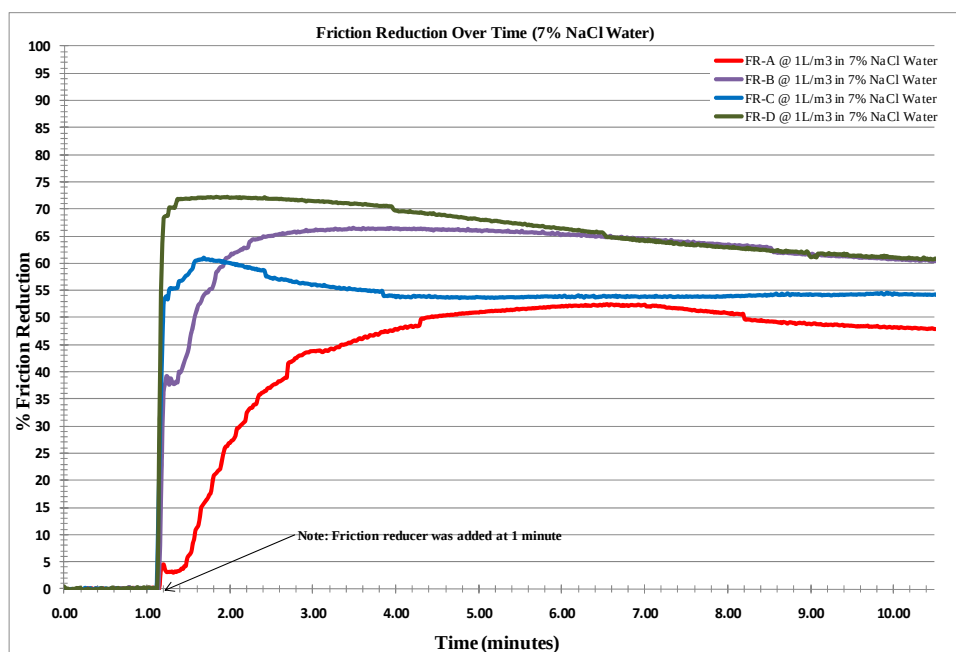


Figure 3- Friction data of friction reducers in 7%NaCl

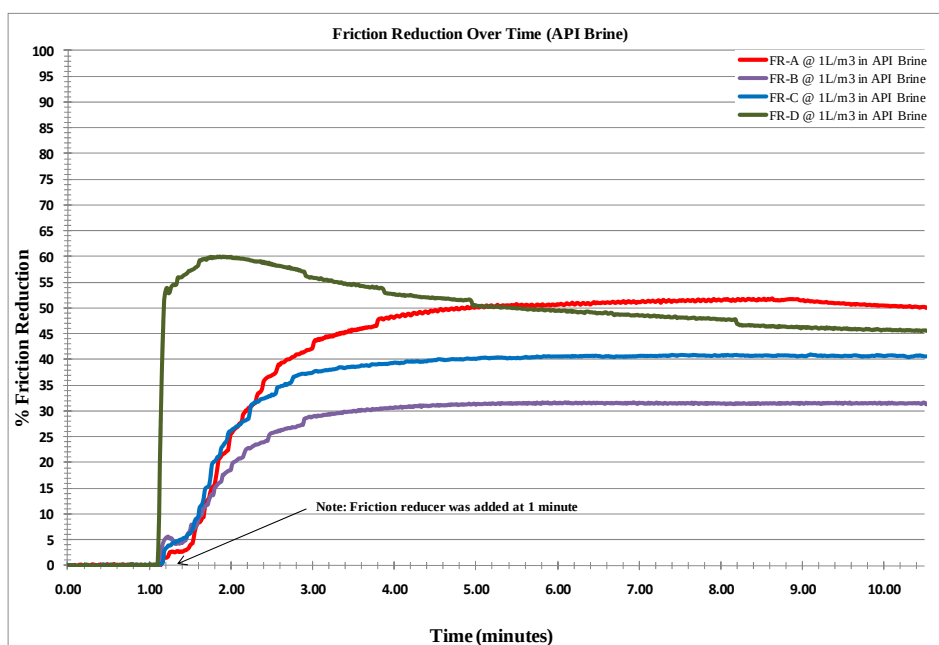


Figure 4- Friction data of friction reducers in API brine

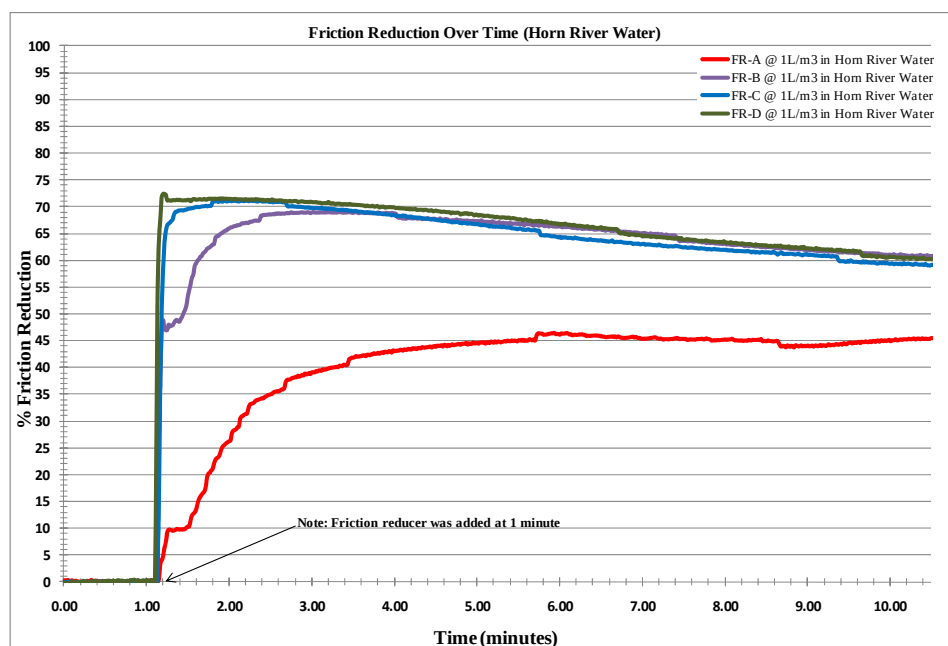


Figure 5- Friction data of friction reducers in Horn River produced water

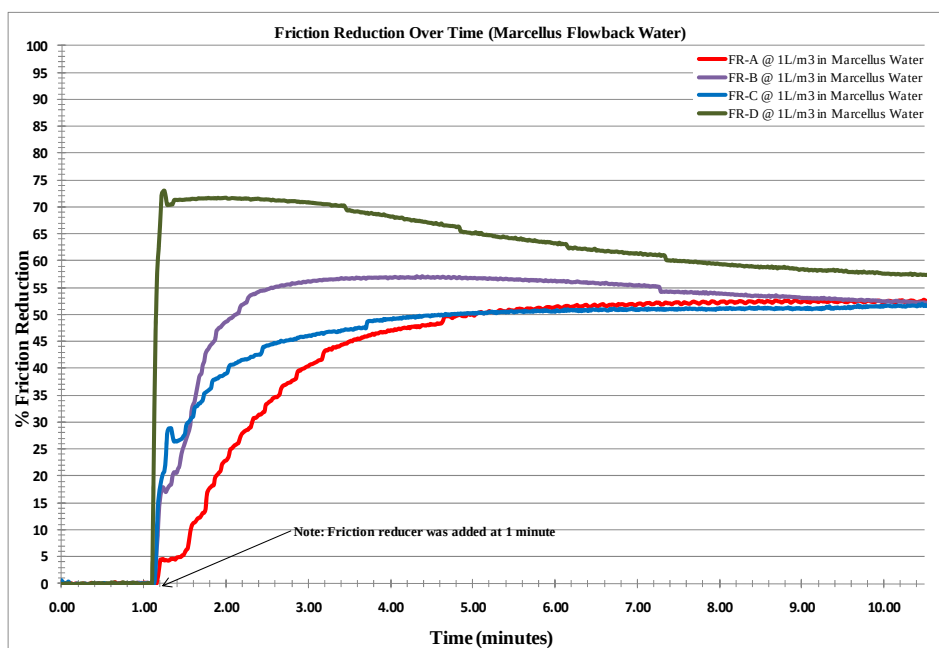


Figure 6- Friction data of friction reducers in Marcellus produced water

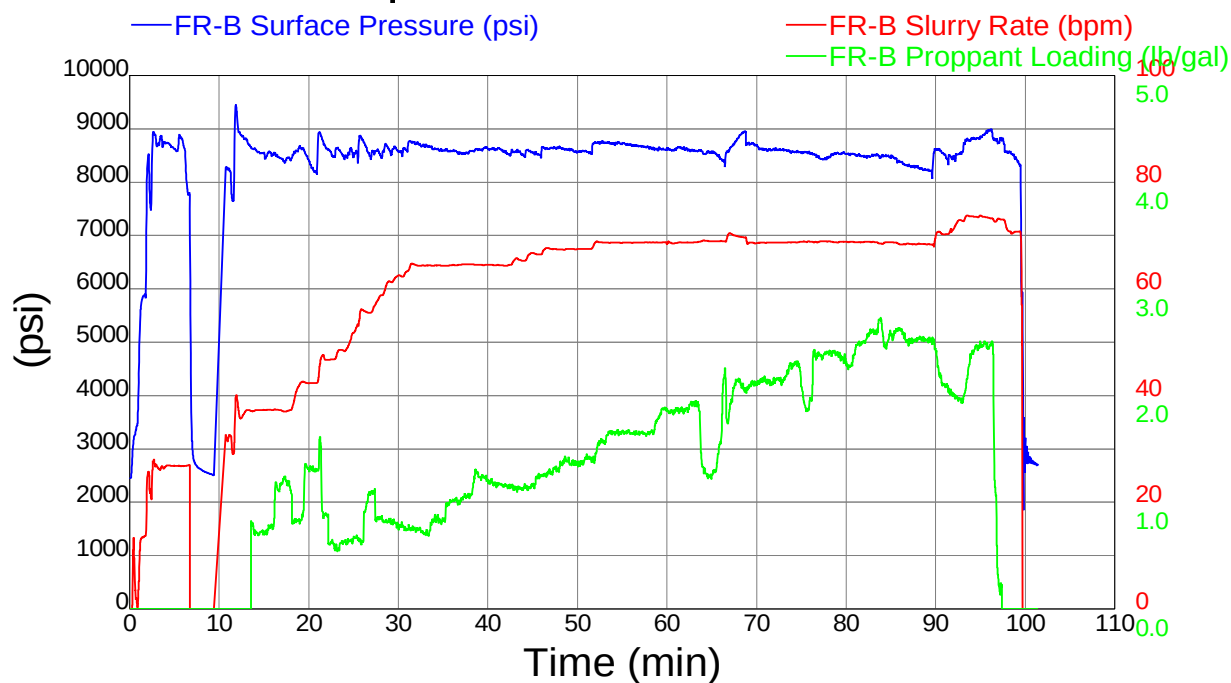


Figure 7 - Field Example FR-B in Fresh Water

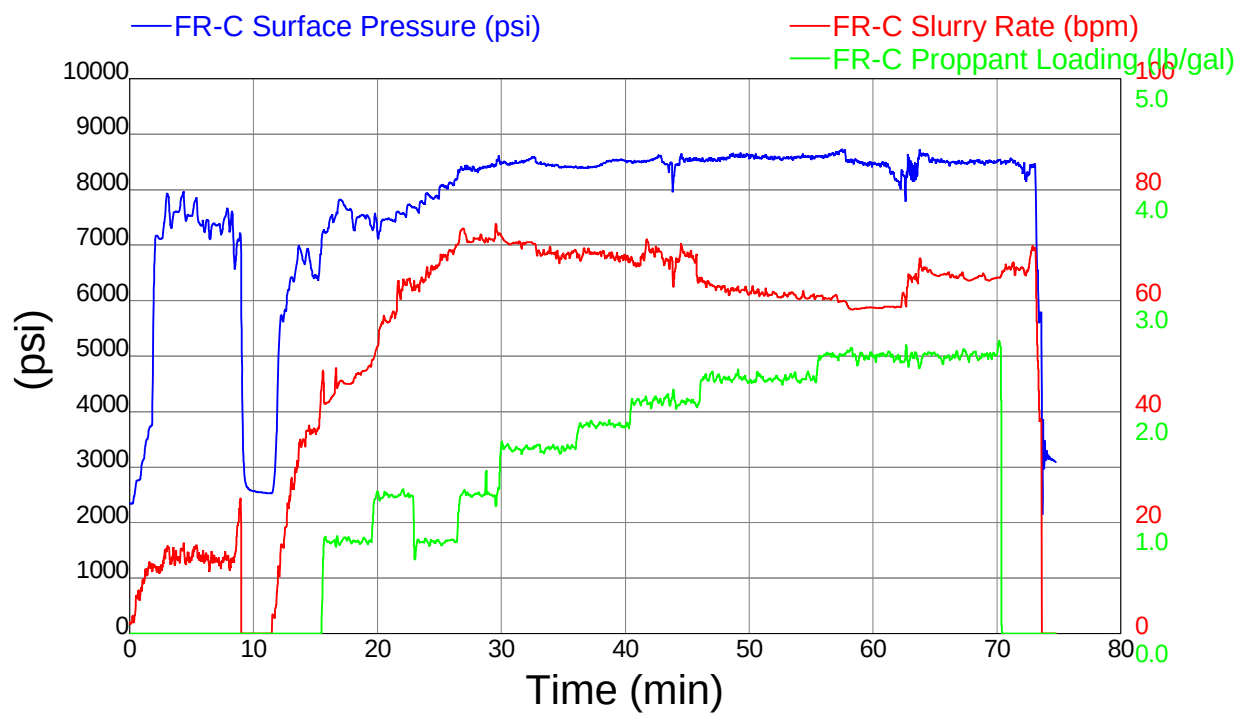


Figure 8 - Field Example FR-C in 3:1 Recycled Water

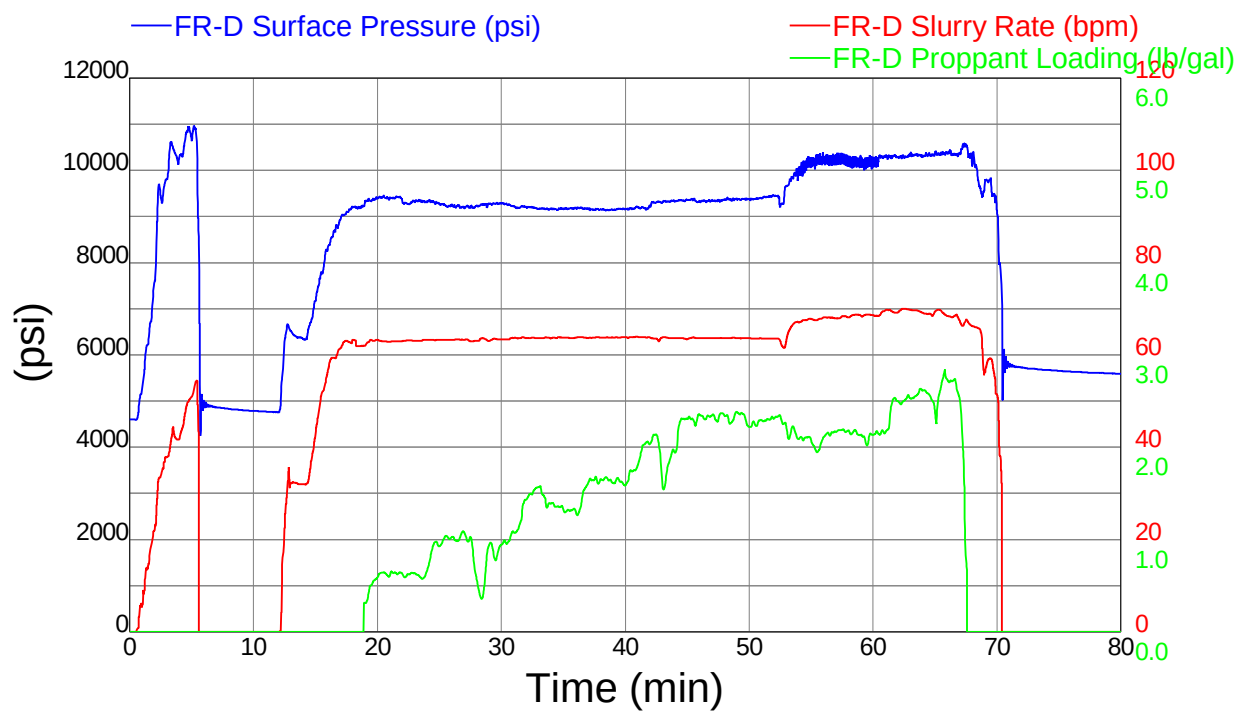


Figure 9 - Field Example FR-D Recycled Water