

High Temperature Coil Tubing Drilling Fluid

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Abstract

Coil tubing drilling is an unconventional drilling technology, typically utilized in complicated environments such as re-entry drilling, slim hole configurations, underbalanced drilling, managed pressure drilling, etc.

Designing a coil tubing drilling fluid for high temperature applications can be challenging. In addition to fluid stability at high temperature, the fluid must provide hole cleaning at low shear rate, minimize pressure loss through the circulating system, maximize the weight transfer to the bit, and minimize whole fluid invasion into permeable rock matrices.

A newly developed high temperature water-based fluid system was formulated to provide enhanced rheological profiles and fluid loss control required for coil tubing drilling applications. The system is based on a novel, branched synthetic polymer, which provides a shear-thinning rheological profile suitable for coil tubing applications and exhibits required temperature stability characteristics. Formation damage potential was also a key aspect in the design and qualification of this fluid.

This paper summarizes the fluid design process, laboratory qualification and verification, as well as summarizes a recent field application, where the new high temperature polymer-based system was successfully deployed as a high temperature coil tubing drilling fluid.

Introduction

Coil tubing drilling is a drilling technology commonly used to address challenges associated with small footprint requirements of limited space environments of offshore platforms, tight clearances associated with conducting operations on existing wells with small casing configurations and/or thru tubing applications(1,2), and economically sensitive operations for which traditional rotary drilling applications would not have been viable. Also included in the feasibility studies to determine the viability of a coil tubing project, is the

drilling fluid selection and qualification study.

This paper details the development and qualification of a coil tubing drilling fluid system which addresses properties specific to coil tubing applications, in particular;

- A rheological profile that comprises both low, high-end rheologies and high, low-end rheologies would be crucial providing sufficient suspension and cuttings transport qualities to optimize hole cleaning in a non-rotating environment
- Achieve density in a solids free environment by utilizing soluble salts to provide density and minimize hydraulic friction and associated circulating pressures
- Provide elevated low shear rate viscosity to minimize fluid leak off (invasion) into permeable zones in a solids free environment
- Possess low coefficient of friction (CoF) and, if required, be compatible with lubricants in order to minimize mechanical friction, maximizing weight transfer to bit and minimizing potential for sinusoidal/helical lock up.
- Provide inhibition characteristics toward shale zones anticipated to be encountered immediately above, and interbedded within the target producing sands.

Retain a low potential for formation damage, maximizing final hydrocarbon productivity in the open hole completed configuration.

While satisfying the requirements above, further complexity was introduced into the qualification process as the anticipated bottom hole temperature (BHT) was significantly high, 330 °F. This downhole condition dramatically impacted the design process as polymers common to coil tubing drilling applications: Welan Gum, Diutan Gum, and Xanthan Gum, would undergo thermally induced degradation at temperatures far lower than the anticipated bottom hole temperature(3). Additionally, synthetic polymers currently available in the oilfield, although stable at the anticipated bottom hole temperature, would not provide the optimized rheological profile required for coil tubing drilling. In order to address this particular design hurdle, a novel synthetic polymer was developed of sufficient molecular weight and branched

structure required to provide the rheological profile required and remain stable at the anticipated bottom hole temperatures. In addition, the polymer showed little impact of varying salinity, further confirming application in the solids free, brine based environment required. Besides being temperature stable, the novel synthetic polymer also showed little variance in rheological properties while subjected to varying temperature and pressure combinations corresponding to those that would be encountered during drilling operations.

As detailed in this paper, laboratory data is presented which confirms the applicability of the novel synthetic polymer, as well as the overall qualification of the final fluid formulation. In addition, data is presented acquired from recent field trials which further corroborates performance of the novel synthetic polymer, as well as the final fluid formulation.

High Temperature Polymer- Development

Xanthan, Diutan and HEC (Hydroxy Ethyl Cellulose) are the conventional biopolymers used for coil tubing drilling and interventions (4,5). At temperature higher than 300 °F, these polymers undergo hydrolytic and oxidation process and lose their stability. Stabilizing components such as oxygen scavengers, free-radical scavengers, pH buffers may extend the thermal stability of biopolymer to a certain extent but it is not the final solution. Limitations of biopolymers in high temperature environments initiated the development of a high temperature polymer. The development process begins with searching for biopolymer alternatives stable above 300°F. Synthetic polymers typically have a higher temperature tolerance and better thermal stability than conventional biopolymers. However, most of the commercially available synthetic polymers have demonstrated limitations such as minimal low-shear rheology, high temperature gelation, and poor suspension properties due to its linear structure. The newly developed polymer was subsequently developed to overcome the limitations of linear synthetic polymers. The polymer is a fully customized branched synthetic co-polymer. The branched nature of the co-polymer viscosifies in the common oil field brines and provides excellent suspension properties, increased low shear rate viscosity and reduced in sag potential while maintaining thermal resistant characteristics.

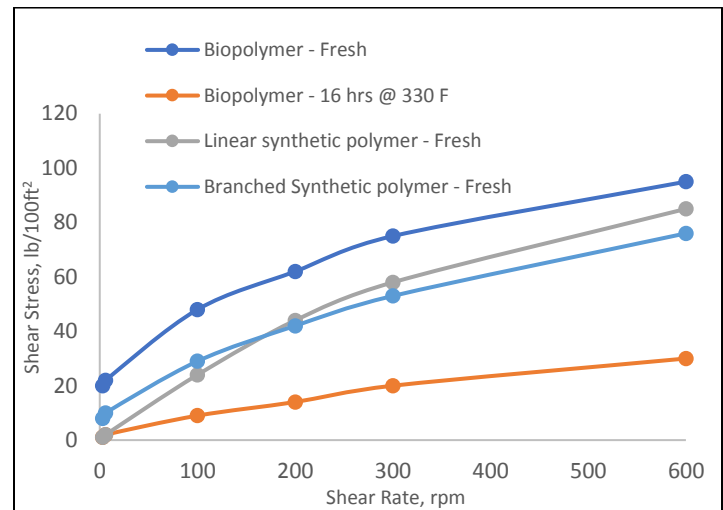


Figure: 1 Rheological Profiles and Temperature Stability of three different polymers

Figure:1 compares the rheological properties of biopolymer, commercially available synthetic polymer and newly developed branched synthetic polymer. As demonstrated, the low end rheologies (a relative indicator for hole cleaning capacity) was compared for three different polymers; 1) Biopolymer, 2) Linear Synthetic polymer and 3) Branched synthetic polymer (newly developed). The three selected polymers were mixed in monovalent brine (low density) at concentrations required to yield similar high end rheologies (Plastic Viscosity, cps). Biopolymers like Xanthan and Diutan provide good low-end rheology yielding approximately 20 lb/100ft², more than sufficient for coil tubing drilling applications, but after heat exposure (16 hours heat aged at 330 °F), the fluid degrades significantly with the low-end rheology becoming 0 lb/100ft². Even in the presence of thermal stabilizers, these biopolymers didn't maintain their rheological profiles. Commercially available synthetic polymers (common to the oil field) were tested as well. As expected their thermal stability was significantly superior to the biopolymers but because of their linear structure, they did not provide low end rheology required for coil tubing operations. The newly developed branched synthetic polymer was synthesized to overcome the above referenced limitations; the fluid is stable and provides required low-end rheology needed for coil tubing operations.

The other critical factor for fluid design in coil tubing operation is minimizing the friction pressure (impacting circulating/system pressure). Shear stresses at elevated shear rates (high end rheology) have the largest impact on circulating pressure. Considering overall reel lengths, typical coil tubing OD's (Outer diameter) & ID's (Inside diameter) and tight clearance of wellbore configuration, minimizing hydraulic friction played an important role in the polymer development.

Biopolymers generally provide low-high end rheologies, commonly resulting in low circulating pressures in coil tubing environments. In contrast, linear synthetic polymers normally have significantly elevated high end rheologies with relatively low-low end rheologies. This characteristic suggests that the hydraulic friction generated by a linear synthetic polymer in coil tubing environment, will lead to excessive circulating pressures. Because of its branched nature, the newly developed synthetic polymer provides low-high end rheologies (optimum for coil tubing environments), while yielding low end rheologies enough for coil tubing applications (cuttings transport). As demonstrated in the graphic below (Figure:2) plastic viscosity (a relative indicator high end rheology) was compared for three different polymers; 1) Biopolymer, 2) Linear Synthetic polymer and 3) branched synthetic polymer (newly developed). The three selected polymers were mixed in monovalent brine (low density) at concentrations required to yield similar low end rheologies. The resultant high end rheologies (Plastic Viscosity) measurements showed that the high end rheologies of newly developed branched synthetic polymer were similar to those of biopolymer, while the high end rheologies of linear synthetic polymer were excessive, far greater than those of biopolymer and branched newly developed synthetic polymer.

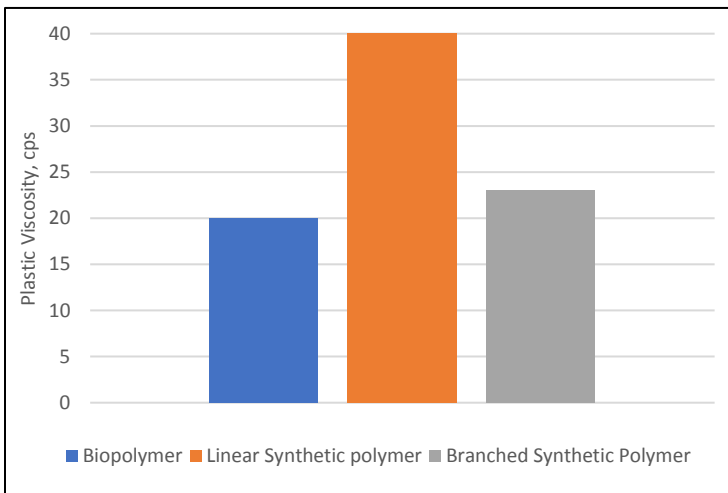


Figure 2: High End Rheology Comparison of 3 different polymers

From the rheological studies, it clearly shows that linear synthetic polymers are not suitable as viscosifiers for coil tubing operations. Furthermore, the temperature stability of typical biopolymers limits their applications. Thus, the newly developed branched synthetic polymer was selected as the primary viscosifier candidate and further qualification testing solely focused on this product.

Table: 1 shows the excellent thermal stability behavior of the branched synthetic polymer. The fluid was formulated by

mixing 8 lb/bbl of the polymer in monovalent brine. The rheology was measured in a rotational viscometer at 120 °F before and after 16 hours and 48 hours static heat aged at 330 °F.

Table 1: Long term stability of branched synthetic polymer

| | Fresh Fluid | 16 hours static aged at 330 °F | 48 hours static aged at 330 °F |
|-------------------------------|-------------|--------------------------------|--------------------------------|
| 600 | 76 | 77 | 78 |
| 300 | 53 | 52 | 54 |
| 200 | 42 | 42 | 43 |
| 100 | 29 | 29 | 30 |
| 6 | 9 | 8 | 9 |
| 3 | 7 | 6 | 7 |
| 10 seconds Gel, lb/100 sq. ft | 7 | 6 | 7 |
| 10 minutes Gel, lb/100 sq. ft | 7 | 6 | 7 |
| PV, cP | 23 | 25 | 24 |
| YP, lb/100 sq. ft | 30 | 27 | 30 |
| LSRV @ 0.3 rpm, cP | 35000 | 36292 | 36492 |

From above, the rheologies are practically identical between initial and after 48 hours static aged (330 °F) fluids. This clearly indicates that the branched synthetic polymer has excellent thermal stability.

Another key factor in selecting the appropriate polymer for coil tubing operations is the ability to provide elevated and stable low shear rate viscosity (LSRV). Elevated low shear rate viscosities, typically measured at 0.3 rpm (0.06 sec⁻¹) are critical fluid parameters they correlate to the fluids capability to suspend the drill solids, especially in wide annuli between coil and original casing. Furthermore, elevated LSRV fluids (formulated in solids free format optimal for coil tubing drilling) control invasion of filtrates into the formation by creating a high differential pressure gradient in the near wellbore area of the rock matrix. As fluid leaks off radially into the formation, the shear rate decreases, and the elevated

viscosity generates hydraulic friction which prevents further penetration. The LSRV of the branched synthetic polymer maintained above 35,000 cp even after heat aged the fluid at temperature for 48 hours.

HTHP Rheology

High temperature rheology of newly developed branched synthetic polymer was measured in rotational rheometer capable of measuring rheologies at varying temperature and pressure environments. A fluid was formulated with 8 lb/bbl polymer concentration, mixed in low density monovalent brine. The formulation was dynamically aged at 330 °F for 16 hours, after which, HTHP rheology was measured at varying pressure and temperature combinations. The results are displayed in table-2 below.

Table 2 data shows that the high-end rheology of the fluid thins down with temperature and pressure but low-end rheology (3 rpm) of the fluid maintained 5 and above even at higher temperature. It is the excellent properties for coil tubing operations because the reduction of high-end rheology (Plastic Viscosity) helps to reduce the circulating pressure. No significant changes in 6 & 3 rpm readings (across the temperature and pressure combinations tested) indicate that the fluid has an extremely stable low-end rheology profile across the entire downhole environment.

Table 2: HTHP rheology of branched synthetic polymer-based fluid

| Temperature | 120°F | 200°F | 250°F | 300°F | 330°F |
|-------------------|-------|-------|-------|-------|-------|
| Pressure, psi | 0 | 3000 | 5000 | 7500 | 10000 |
| 600 | 89 | 62 | 51 | 45 | 39 |
| 300 | 62 | 42 | 35 | 31 | 27 |
| 200 | 49 | 34 | 28 | 24 | 26 |
| 100 | 34 | 23 | 19 | 17 | 15 |
| 6 | 10 | 8 | 6 | 5 | 7 |
| 3 | 8 | 6 | 5 | 5 | 7 |
| PV, cP | 27 | 20 | 16 | 14 | 12 |
| YP, lb/100 sq. ft | 35 | 22 | 19 | 17 | 15 |

Coefficient of Friction

Coefficient of Friction (CoF) is also an important property for coil tubing drilling operations. Fluids and/or additives must have lubricious properties in order to prevent helical lock-up and adequately transfer weight to bit. Lubricity testing (steel on steel) was carried out via torque measurements at varying side force loadings.

A blank test fluid (newly developed branched synthetic polymer in low density monovalent brine) was tested along with additions of three common lubricants at various concentrations. The blank fluid (no lubricant) yielded coefficient of friction of less than 0.12, which is low compared to typical polymer-based systems. In the event that more lubricity is required and to verify lubricant compatibility, three different lubricants were tested. All three lubricants showed no in-compatibility with the fluid (no greasing or cheeing observed). As well, all lubricants tested reduced the CoF, indicating that the lubricant performance (of the chemistries tested) is not compromised in the presence of newly developed branched synthetic polymer.

Heat ageing the fluid treated with various lubricants showed no reductions in the fluid properties, indicating that the polymer is still resilient and robust in the presence of lubricants. As well, CoF's remained constant.

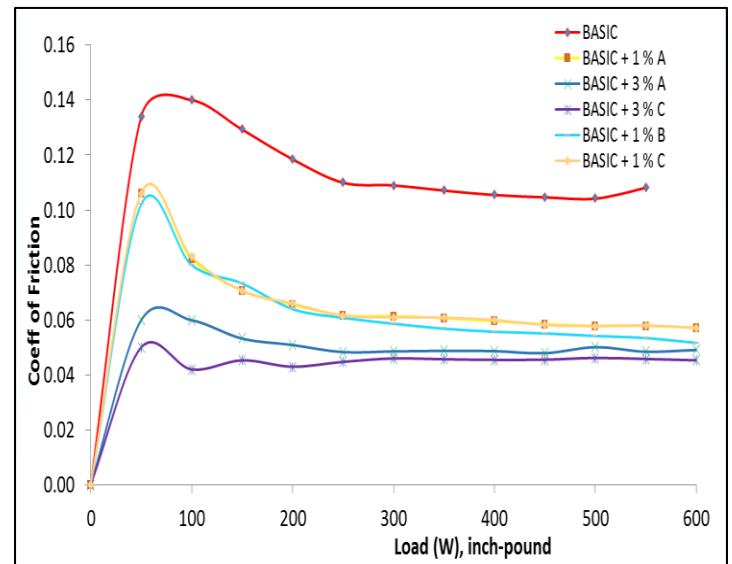


Figure 3: Coefficient of Friction of branched synthetic polymer-based fluid with and without different lubricants.

Shale Inhibition

The newly developed system was tested for shale inhibition tests. The shale cuttings from the reservoir section were received and used for the shale inhibition tests. The dispersion test was used to determine the effectiveness of inhibitor additives to maintain the integrity of the cuttings and

minimize the interaction of fluids with the shale sections during drilling and completion operations. The test provides long-term exposure of the shale to the fluid under mild agitation. Under such conditions, dispersion of the shale into the fluid will occur depending on the tendency of the shale to disperse when exposed to the inhibitive properties of the fluid.

The shale cuttings were mixed with newly developed branched synthetic polymer based fluid (with & without 1 volume% of lubricant C) and hot rolled for 16 hours at 330 °F. The result of the shale dispersion test is shown in the below figures- 4 & 5. The recoveries of the shale cuttings from the fluids are greater than 90% and the shale cuttings are intact after the tests. The results of the dispersion test indicates that the fluid has great control over the dispersion tendency of the shale cuttings and also the lubricant didn't impact the result.

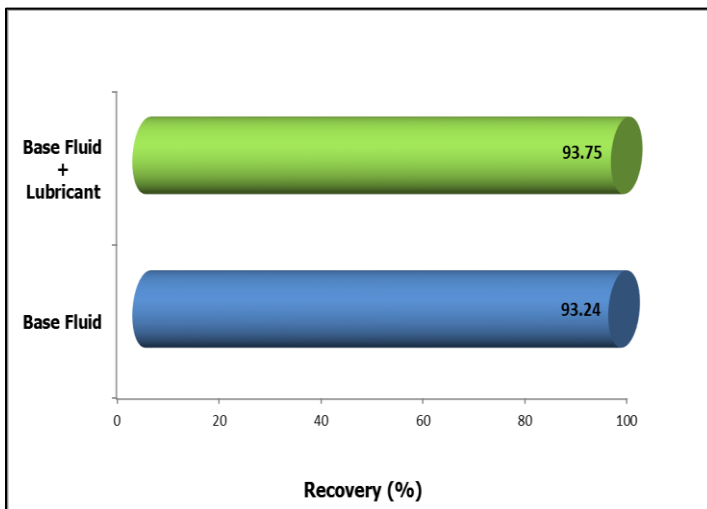


Figure 4: Percentage of Shale Recovery from the fluid with and without lubricant



Figure 5: Shale cuttings after the shale recovery tests

Linear swell tests were conducted to measure the volumetric expansion of a reconstituted shale sample (wafer) while exposed to the fluids under temperature (330 °F) and

pressure (300 psi). The machine helps to determine shale hydration by measuring an increase in wafer thickness over time. Shales that are prone to swelling can cause drilling problems like stuck pipe, tight hole, washout and sloughing.

The Figure 6 results showed that very little of swelling (around 5%) was observed, and the swelling would be significantly less downhole where overburden pressures are substantial.

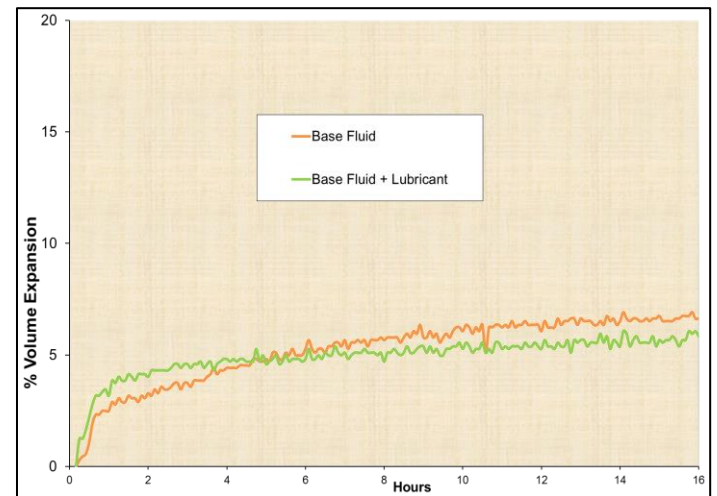


Figure 6: Linear swell tests of branched synthetic polymer fluid

Overall, the branched synthetic polymer-based fluid showed great control over shale dispersion and swelling.

Hydraulics

As part of design and qualification process, properties from an optimized fluid formulation, in particular rheology measurements performed at ambient, and under HTHP conditions were obtained and subsequently utilized to perform hydraulic simulations. Along with the rheology data, coil tubing dimensions, wellbore configurations, surface equipment details, BHA characteristics (dimensions as well as flow rate vs pressure drop data).

In-house hydraulics simulation software was used to estimate the pump pressure and flow characteristics for the newly developed branched synthetic polymer-based system. Figure-7 shows the relationship between the flow rate and the pump pressure predicted by the hydraulics software. As hole cleaning and down hole tool functionality were optimized at 100 gal/min, the associated circulating pressure was predicted to be less than 4000 psi which was well within the limits of equipment capabilities.

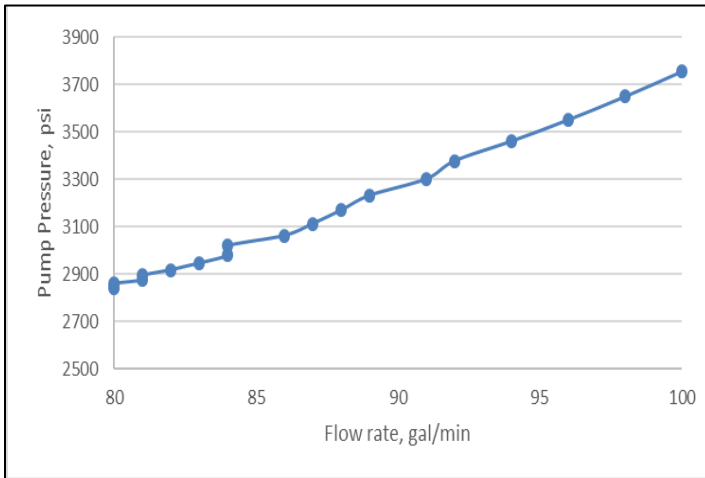


Figure 7: Circulating pressure prediction vs flow rate

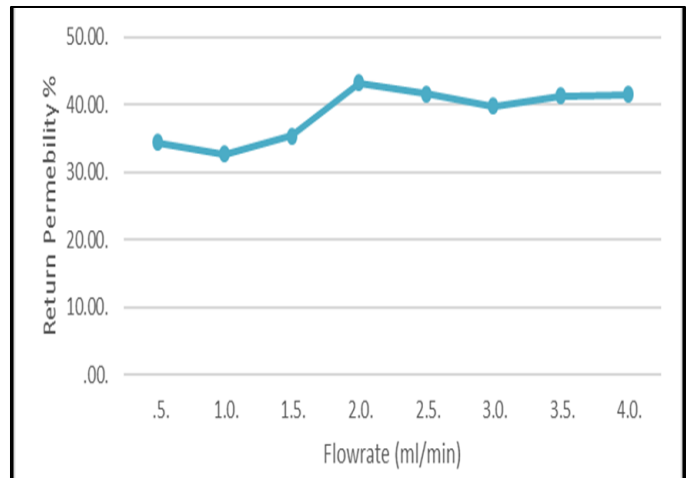


Figure 8: Return permeability of branched polymer based system

Formation Damage Tests

The laboratory testing and simulation results showed that the newly developed branched synthetic polymer has the right properties to be used for coil tubing operations. To address the concern of potential formation damage caused by synthetic polymers, further laboratory testing was undertaken in the form of return permeability measurements. Generally, formation damage associated with solids free fluid systems can be relatively high due to the viscous nature of the invading fluid and the resultant friction pressures within rock matrix. As well there is a potential for adhesion of the synthetic polymer and the internal surfaces of the pore network.

Return permeability testing was undertaken using actual reservoir core material, exposing the core to the candidate drilling fluid under downhole conditions (500 psi overbalance pressure, resulting in 2 pore volumes injection). The resulting return permeability of the newly developed synthetic polymer-based system was approximately 40%, which is considered as acceptable return permeability for solid free system regardless of polymer type used (analogous to xanthan or Diutan based systems). The return permeability data is presented in the figure-8.

Field Application

The new high temperature water-based coil tubing fluid system was field trialed during a re-entry operation of a multi-lateral slim-hole well. The system was used to drill lateral sections with expected bottom-hole static temperature of 330°F using coil tubing drilling.

Liquid Mud Plant Mixing (LMP)

The final formulation used for LMP mixing is shown in Table-3. And the properties after mixing compared to lab properties are shown in Table-4.

Table 3: The formulation of branched synthetic polymer-based fluid

| Product Name | Concentration |
|----------------------------|---------------|
| 3% KCl brine | 0.906 bbl/bbl |
| 12.5 ppg NaBr | 37.3 lb/bbl |
| Defoamer | 0.35 lb/bbl |
| Branched synthetic polymer | 8.0 lb/bbl |
| pH buffer | 2.0 lb/bbl |
| HT Lubricant | 0.01 bbl/bbl |

Table 4: The rheological property of branched synthetic Polymer-based fluid measured in laboratory and LMP

| Rheology (120 °F) | Lab Fresh Mixed | LMP Fresh Mixed |
|-------------------|-----------------|-----------------|
| 600 | 76 | 77 |
| 300 | 53 | 55 |
| 200 | 42 | 45 |
| 100 | 29 | 32 |
| 6 | 9 | 11 |
| 3 | 7 | 9 |
| PV, cP | 23 | 22 |
| YP, lb/100 sq. ft | 30 | 33 |
| LSRV (120 °F), cP | 37,000 | 39,000 |

A total of 2250 barrels of branched synthetic polymer-based fluid were successfully mixed at the LMP with properties identical to the properties obtained in the lab confirming the mixability of the system.

Milling and Drilling Operations

After killing the well using seawater, the re-entry was initiated by installing a whip stock and milling the casing using the newly developed branched synthetic polymer-based fluid. Table-5 compares standpipe pressure before and after displacing the well to branched synthetic polymer-based fluid. Stand pipe pressure was reduced significantly after displacing the well from sea water to branched synthetic polymer-based fluid before commencing the milling operations.

Table 5: Flow rate vs Stand Pipe Pressure

| Fluid | Flow Rate, gal/min | Stand Pipe Pressure |
|--|--------------------|---------------------|
| Sea Water | 100 | 4270 psi |
| branched synthetic polymer-based fluid | 91 | 3165 psi |

The milling operations were completed without any fluid related issue. The fluid properties remained stable with

excellent hole cleaning and metal swarf transport observed throughout the milling operations.

The open-hole section was drilled to total depth without any drilling fluid related issue. The fluid properties remained stable with no observable signs of polymer degradation (both associated with high shear and high temperature). When required, lubricants were added to optimize weight transfer and avoid helical lockup tendency.

As designed, the elevated low shear rate viscosity helped minimize down hole losses and ensure optimal hole cleaning and cuttings transport. Figure-9 shows LSRV (Low Shear Rate Viscosity) as recorded while drilling.

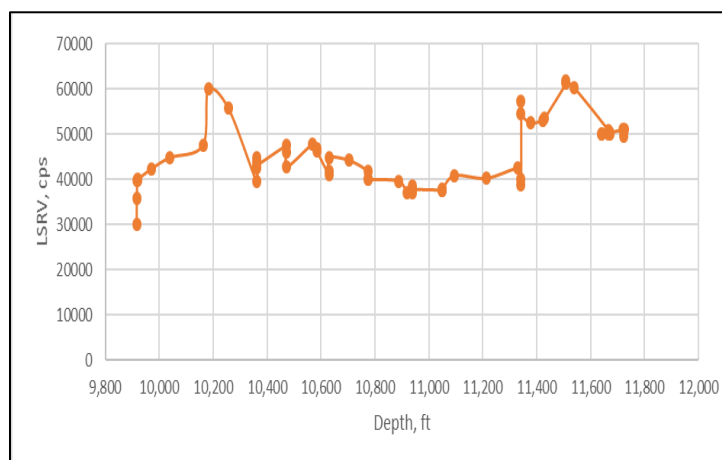


Figure 9: LSRV as recorded while drilling

Figure-10 displays the predicted stand pipe pressure versus recorded pump pressure while drilling. These data proved that the hydraulics simulation was accurate, and the polymer behaved as expected.

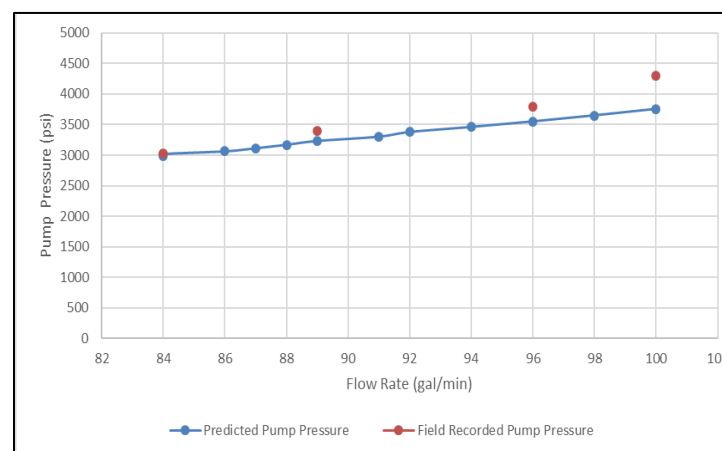


Figure 10: Predicted versus Field recorded pump pressure

At total depth, the well was displaced to branched synthetic polymer-based fluid liner running fluid and the liner was run to bottom without any issue.

After drilling the interval and installing completion equipment, the well was brought onto production with observed flowrates higher than expected with associated drawdowns lower than expected, confirming that the branched synthetic polymer-based fluid did not cause significant formation damage while drilling.

SPE-76903-PA, SPE Drilling & Completion, March 2002.

Conclusion

1. A novel synthetic polymer was successfully developed which is temperature stable and still provides the rheological properties required for coil tubing drilling.
2. Laboratory qualifications confirmed that other critical properties; coefficient of friction, shale inhibition, formation damage potential, were achieved with candidate fluid formulation.
3. Field data confirmed that the polymer is temperature stable and resistant to shear degradation.
4. Hydraulic performance fell within predicted values.

Acknowledgments

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