

## The HP/HT Rheology Evaluation of Spacers

Vivek Goel, Ron Morgan, and Thomas Sodhi, Halliburton

Copyright 2014, AADE

This paper was prepared for presentation at the 2014 AADE Fluids Technical Conference and Exhibition held at the Hilton Houston North Hotel, Houston, Texas, April 15-16, 2014. This conference was sponsored by the American Association of Drilling Engineers. The information presented in this paper does not reflect any position, claim or endorsement made or implied by the American Association of Drilling Engineers, their officers or members. Questions concerning the content of this paper should be directed to the individual(s) listed as author(s) of this work.

### Abstract

It is widely acknowledged that the evaluation of rheological properties of oil-well fluids is important from the standpoint of providing the required circulation pressure and operational parameters for completions operations. Good rheology control is hence a prerequisite for the optimal fluid performance under downhole conditions. As near-surface and sub-surface petroleum and natural gas resources near depletion, there is a demand to dig deeper and into more severe conditions of temperature and pressure, both onshore and offshore, globally. Spacers, used in well cleanup and as cement precursors, can be subjected to high temperature and pressure gradients as they travel downhole. Hence, a rheological evaluation of spacers under conditions of high pressure/high temperature (HP/HT) is important for job design and execution.

During this study, the suspension rheology of moderate-to-high-temperature spacers is evaluated in the parametric space of operational temperature, pressure, density, and yield point (YP). The thermal thinning behavior of the spacers is evaluated until the point of spacer instability. A wide range of densities and initial yield points is used to maximize the relevance to field conditions. The effect of each parameter on the overall suspension rheology is evaluated, thereby providing understanding of the HP/HT rheological behavior of spacers. Such a comprehensive rheological evaluation of spacers incorporating HP/HT and the additional parameters of density and initial YP are expected to be valuable for field engineers.

### Introduction

Deep wells and ultra-deep wells are increasingly being pursued as near-surface and sub-surface petroleum and natural gas reserves near depletion. Along with such exploration comes the exposure of drilling and completion fluids to severe conditions, commonly referred to as HP/HT conditions. Typically, temperatures in excess of 250°F and pressures beyond 10,000 psi constitute the domain of HP/HT operations.

Near-surface and sub-surface rheology of oil-well fluids have been mostly addressed, with the emergence of temperature- and pressure-independent rheological models (e.g., Generalized Herschel-Bulkley model, which encompass other familiar models), such as the power law, Bingham Plastic, Herschel Bulkley, and Casson's model.<sup>1</sup> However for deep and ultra-deep wells, a clearer understanding of the effect

of HP/HT conditions on the flow behavior of oil-well fluids is necessary for providing required circulation pressure and optimal fluid performance under HP/HT conditions.

Some previous excursions have been made in the area of HP/HT rheology, but a rigorous understanding has yet to emerge. For example, a study was conducted that focused on the development of a model for predicting the effects of temperature on viscosity of water-based muds (WBMs).<sup>2</sup> Others developed a method for measuring viscosities of heavy oil mixtures up to 450K and 4,000 kPa.<sup>3</sup> Effects of deep well HP/HT conditions and salinity on rheological properties of WBMs was recently reported.<sup>4</sup> Additionally, selecting the correct rheological model is important to help ensure accuracy, such as the work presented comparing the Generalized Herschel-Bulkley model to the conventional Bingham Plastic model for spacer and spacer/mud mixtures.<sup>5</sup> The use of nanoclays has been previously investigated for their effect on the transport (flow) properties of drilling fluids for HP/HT operations; however, therein the rheological measurements were performed at ambient conditions.<sup>6</sup> Another study probed the effect of HP/HT conditions on the rheology of oil-based drilling fluids using the latest available experimental tools of HP/HT rheology.<sup>7</sup> Yet another attempt has been reported of arriving at a quantitative description of the effect of T, P on the viscosity of a drilling mud with principles adopted from a design of experiments (DoE) perspective.<sup>8</sup> However, despite these limited attempts, a definitive understanding of HP/HT effects on the rheology of oil-well fluids continues to remain elusive for a broad range of drilling fluids and completion fluids, including spacers and cements.

As a completion fluid, the cement slurry is a highly complex material. From a standpoint of suspension rheology, the cement slurry consists of particles with a range of particle sizes, size distributions, shapes, and activities (hence inter-particle interaction effects). The rheology of cement slurry is further convoluted by the effects of heats of hydration and the changing landscape of the particles with hydration kinetics.

The present study is a systematic evaluation of the HP/HT rheology of drilling and completion fluids, focusing on the chemically simpler (compared to a hydrating cement slurry) system of well spacers. Specifically, a medium-temperature spacer was used, with a range of densities and initial YPs (YP evaluated at 80°F as commonly used in the field). The specific goal was to obtain a holistic understanding of the effects of

temperature, pressure, density, and initial YP on the viscometric (viscosity vs. shear rate) behavior of the medium-temperature spacer fluid. Such a holistic understanding would aid an interpretive understanding of the physics of the flow behavior of spacers (low-, medium-, and high-temperature spacers), drilling muds, and cement slurries, hence helping field engineers to better design various fluids for jobs.

## Theory

A technique presented for developing a holistic rheological model for crosslinked fracturing gels was adapted to this study.<sup>9</sup> Applying this technique resulted in the following generalized equation for predicting the impact of shear rate, initial YP, temperature, density, and pressure on the viscosity of spacers tested during this study (Eq. 1):

$$\eta = [\dot{\gamma}] [YP] [T] [\rho] [P] \dots\dots\dots (1)$$

The components in Eq. 1 are defined in Eqs. 2 through 6 as follows:

$$[\dot{\gamma}] = \left\{ \frac{\tau_{0,ref} + K_{hb,ref}(\dot{\gamma})^{n_{hb}}}{\dot{\gamma}} \right\} \dots\dots\dots (2)$$

$$[YP] = \{1 + A_{YP}EXP(k_{YP} * YP)\}^{B_{YP}} \dots\dots\dots (3)$$

$$[T] = \{1 - A_T(T - T_0)\} \dots\dots\dots (4)$$

$$[\rho] = \left( \frac{\rho}{\rho_{avg}} \right)^{n_{\rho}} \dots\dots\dots (5)$$

$$[P] = \text{Dimensionless pressure function} \dots\dots\dots (6)$$

It should be noted that Eq. 2 has units of viscosity, while Eqs. 3 through 6 are dimensionless. Data collected during this study was used to help determine the best fit values for each of the coefficients in Eqs. 2 through 6.

## Experimental

### Material Preparation

A medium-temperature suspension spacer was used during this study. The suspension spacer was water-based. Barite was used as a weighting agent to modify the density as necessary. The spacer and barite were dry blended in various proportions to achieve varying levels of densities and initial YP stresses at 80°F as necessary. After the materials were dry blended, the required amount of deionized (DI) water and defoamer were placed into a standard Waring® blender. The defoamer was added to help prevent air entrainment during the process of blending, and did not present any significant effect on the rheological properties of the spacer material.

The water and defoamer were stirred at ~2000 rev/min and the dry blended mixture was gradually added to the water mix and stirred for ~5 min. The spacer prepared was used for performing the rheology measurements.

The laboratory practice for mixing the spacer with Barite, water, and defoamer is recommended to reduce the shear imparted to the viscosifier. However, this mixing procedure

does not cause any deviations in rheological behavior from the spacer mixed following the API Recommended Practice 10B-2.<sup>10</sup>

### Equipment

Rheology measurements were performed on Couette-type HP/HT rheometer—Chandler 5550. The Chandler 5550 equipment has an operating pressure range of ambient to 2000 psi and an operating temperature range with an upper limit of 500°F. The geometry used for the Couette-type flow was the smooth bob-sleeve (R1-XB5) on the Chandler 5550.

### Variables Considered

The shear speeds covered during the rheology measurements ranged from 3 to 300 rev/min (typical shear stress measurements were performed at 3, 6, 10, 20, 30, 60, 100, 200, and 300 rev/min). The 600 rev/min measurement was avoided, following the API recommended practice 10B<sup>10</sup> for measuring the rheology of oil-well fluids.

The temperatures for rheology measurements ranged from 80 to approximately 260°F. The spacer was determined to be thermally stable (by way of rheology data) to a little under 300°F. However, to avoid complications of thermal instability signatures on the rheology data, it was deemed advisable to investigate data up to a temperature of approximately 260°F.

The densities for the spacer ranged from 10 to 19 ppg. The 10 ppg was deemed low enough without encountering settling difficulties, while the 19 ppg represented the limit when difficulty in mixing was encountered. Density variations measured between a standard laboratory pressurized mud balance and a pycnometer (Pentapyc 5200e model) were in the range of 0.2 to 0.3 ppg. This slight variation in absolute density does not present a problem in the analysis presented in this manuscript.

The YP range for the spacer varied from 20 YP (measured at surface conditions. Note that units of YP are lb<sub>f</sub>/100 ft<sup>2</sup>) to 70 YP. The reason for choosing these limits was the same as that for the density range. A minimum of 20 YP was deemed sufficient to circumvent settling issues, while 70 YP began to pose mixability difficulty. YP variations from rheological modeling were in the range of 2 to 3 YP, which does not present a problem with respect to the analysis presented in this manuscript.

### Rheology Measurements

A freshly prepared spacer slurry was placed in the cup and affixed to the rotor fixture on the rheometer. The sample was sheared at 150 rev/min (= 127.54 s<sup>-1</sup> on the R1-XB5 stator) for 15 min on the Chandler 5550 (to allow the temperature to equilibrate to the initial temperature of 80°F) before shear stress measurements were determined. Shear stress data were recorded following an upward shear ramp program from 3 rev/min (= 2.55 s<sup>-1</sup> on the R1-XB5 stator) to 300 rev/min (= 255.09 s<sup>-1</sup> on the R1-XB5 stator) and back down to 3 rev/min. Data (typically 2 to 3 data points) were collected at each individual rev/min for 30 sec, and the average of the 30-sec measurement was determined as the representative

measurement. During all cases, the average deviation between data points was less than 1%, hence, error bars are not shown in the data. The sample was then sheared again at the previous rate of 150 rev/min, while the heater ramped to the next temperature at approximately a rate of 1°F/min.

### Data Analysis

Upward and downward ramp shear stress data were collected at each measured temperature and pressure. While the upward and downward ramp shear stress data showed some hysteresis (indicating thixotropy), the hysteresis was not large enough to warrant a separate analysis of the hysteresis loop as is performed elsewhere<sup>11</sup>. Hence, only the downward ramp shear stress data were used (as is common practice), and the corresponding viscosity data as a function of shear rate were evaluated (viscometric curve).

### Test Results and Discussion

The obtained rheological data of the suspension spacer was evaluated in a sequential manner, beginning with the simplest consideration of the effect of the shear rate on the viscometric data. The effect of the temperature was then added to the viscometric data. The level of complexity was increased by evaluating the effect of density on the temperature-dependent viscometric data, followed by the effect of YP on the temperature-dependent viscometric data. Lastly, an excursion was made into the effects of pressure on the viscometric data.

#### Effect of Shear Rate—Viscometric Data (Maintaining YP, Temperature, Density, and Pressure Constant)

Fig. 1 illustrates the viscometric data for the spacer with 10 ppg density and 20 YP at 80°F. Note that the pressure is maintained at 500 ± 20 psi throughout the measurement.

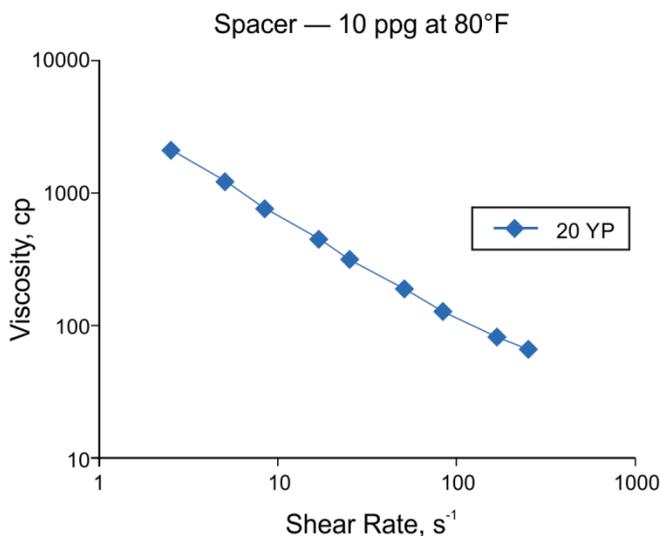


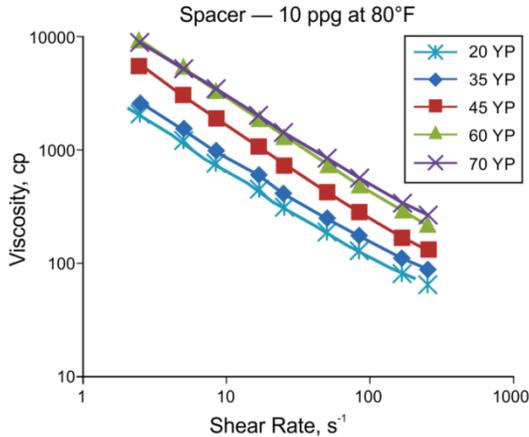
Fig. 1—Viscometric curve (viscosity vs. shear rate) of spacer at 10 ppg density and 20 lb<sub>f</sub>/100 ft<sup>2</sup> YP—commonly referred to as 20 YP) at 80°F. The pressure is maintained at 500 ± 20 psi throughout the measurement.

It is clear from Fig. 1 that the material exhibits shear-thinning behavior. The spacer contains anisotropic particles and a viscosifying polymer, all of which can exhibit a directional orientation based on the shear applied. As a result of possible directional orientation, such shear-thinning behavior is not surprising. This phenomenon of a microstructural rearrangement causing thixotropy (reversible shear-thinning behavior because of structural deformation) has also been indicated as a possible mechanism for shear-thinning behavior of materials previously<sup>12</sup>.

#### Effect of YP on Viscometric Data (Maintaining Temperature, Density, and Pressure Constant)

Following the establishment of the viscometric curve for the base spacer of 10 ppg density at 80°F, the effect of YP on the viscometric data at a constant density and constant temperature was explored. Fig. 2 illustrates the set of viscometric curves for the base spacer of 10 ppg density at 80°F. Note that the pressure was maintained at 500 ± 20 psi throughout the measurement. The viscometric curve at 20 YP (lowest YP probed) is also shown for reference. Several observations can be drawn from the data:

- The shear thinning nature of the spacer was maintained across all YPs from 20 lb<sub>f</sub>/100 ft<sup>2</sup> (lowest probed) to 70 lb<sub>f</sub>/100 ft<sup>2</sup> (highest probed).
- The linear shear thinning nature of the viscometric curve (i.e., the reduction of viscosity with shear rate) was maintained across all YPs probed.
- As the YP of the spacer was increased, the viscosity of the spacer was increased across all shear rates probed—from 3 rev/min (= 2.55 s<sup>-1</sup> on the R1-XB5 stator) to 300 rev/min (= 255.09 s<sup>-1</sup> on the R1-XB5 stator).
- The viscosity increase with increasing YP was rapid between 35 and 60 YP. At the highest YP of 70, the viscosity increase slowed down. Hitting a maximum deflection on the bob reading or encountering mixability issues was ruled out because neither of these was observed during testing.



**Fig. 2—Effect of YP (at 80°F) on viscometric curves at 80°F for spacer of 10 ppg. The pressure was maintained at  $500 \pm 20$  psi throughout the measurement.**

Changes in YP were brought about by adjusting the ratio of the dry spacer blend and barite. Any change in the ratio left the overall density unchanged at 10 ppg. The absolute number of different particle types and the polymers, however, changed as the ratio of spacer and barite changed. Because the viscometric curve would be expected to be a function of several variables, including particle size, shape, density, particle-particle, particle-polymer, and polymer-polymer interaction, the viscometric curves can be expected to change shape as the blend ratio changes. However, the observations of the viscometric curves reveal otherwise. The shape of the viscometric curve is similar across the YPs probed. From a field perspective, this lends to an ease of extrapolation of field behavior when moving across YP; but, from a scientific understanding, this would be unexpected.

Two important conclusions of use to field applications can be drawn:

- As the YP of the spacer is increased, the viscosity increases as well, but not in a direct proportion.
- The nature of the viscometric curve (at constant density, temperature, and pressure) remains unchanged across a wide range of YPs relevant to field application.

### **Effect of Temperature on YP Effects on Viscometric Data (Maintaining Density and Pressure Constant)**

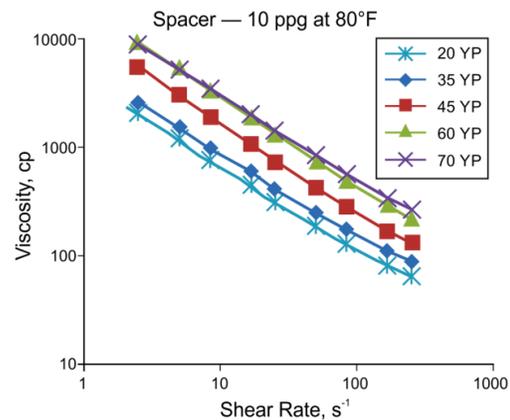
The observation from the previous section that changing the YP of the spacer has no noticeable effect on the linear nature (shape) of the viscometric curve results in the next level of probing, which is how the variables of temperature, density, and pressure play a role in determining the rheology. Temperature would be expected to directly affect interaction potentials and change relaxation times of the particles and polymers. This would result in a change of not only the viscosity of the spacer, but would also be expected to have an impact on the viscometric curve of the spacer. Interaction potentials are usually expressed so that with increases in

temperature, the interaction potentials fall steeply ( $U(r) \sim -f(r)/k_B T$ ). Hence, an increase in temperature can be expected to cause changes in interaction potentials, which would change how the particles and polymers interact with one another, ultimately reflecting in a change of the viscometric curve. This change of the viscometric curve would not only be expected to reflect on changed viscosities, but also potentially a change in the shape of the viscometric curve.

In the expression for the interaction potentials widely considered for colloids and polymeric systems,  $f(r)$  is a radial function that has been thus-far expressed by several means, such as in the Lennard-Jones potential, the Yukawa form, etc. Several excellent resources abound in literature for the various interaction potentials that are considered, which is not under the purview of this present manuscript.

**Fig. 3** illustrates the effect of temperature on the YP-dependent viscometric curves. The data shown is for a spacer density of 10 ppg. Note that the pressure is maintained at  $500 \pm 20$  psi throughout the measurement. The viscometric curves at 80°F (lowest temperature probed) are also shown for reference (Fig. 3(a)). When comparing Figs. 3(a), (b), (c), and (d), several observations can be drawn:

- From the lowest temperature probed of 80°F up to approximately 180°F (sample temperature was 178°F, as shown in Fig. 3(c)), the viscosity data remained at approximately similar values.
- The viscometric data at 258°F fell lower than the values at the previous temperatures.
- The shape of the viscometric curves remained the same, independent of temperature.
- The observation that the viscosity increase with increasing YP is rapid between 35 and 60 YP, remains the same as previously discussed and is evident for all the temperatures probed. This is particularly manifested for the data at 258°F, where the 20 and 35 YP data are not far apart from one another, as are the 60 and 70 YP data. Between the 35 and 60 YP data is a relatively steep increase of viscosity with YP, noting that the shape of the viscometric curve remains unchanged throughout.



**Fig. 3(a)**

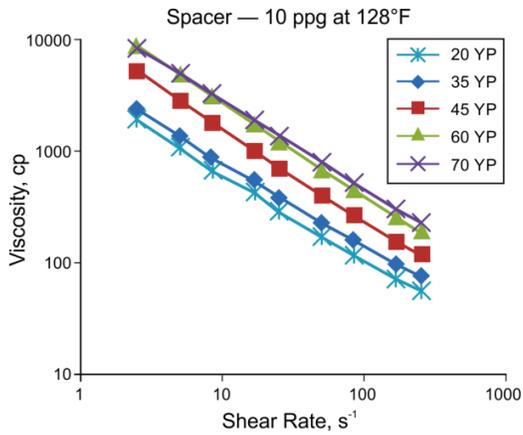


Fig. 3(b)

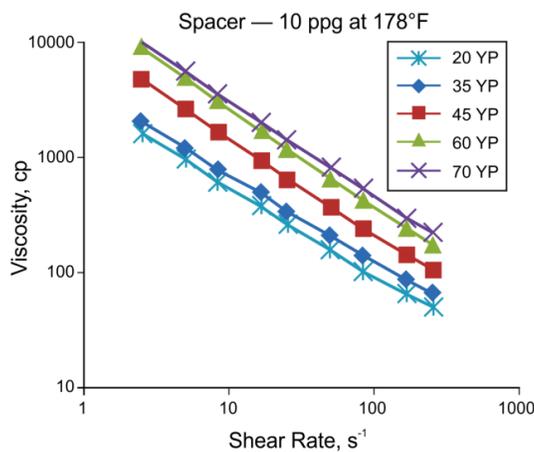


Fig. 3(c)

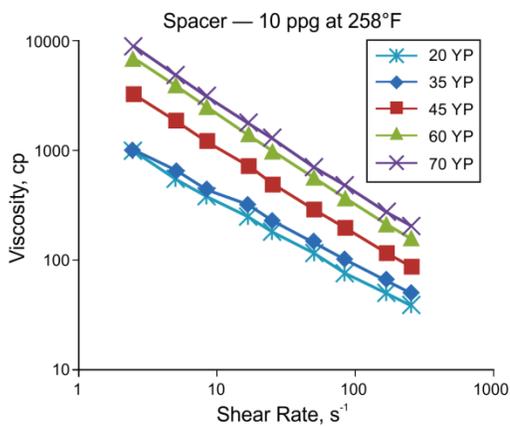


Fig. 3(d)

**Fig. 3—Thermal effect on YP-dependent viscometric curves, for spacer of 10 ppg. The pressure was maintained at  $500 \pm 20$  psi throughout the measurement.**

As previously mentioned, an increase in temperature would be expected to cause a reduction in the inter-particle potentials, thereby leading to changes in viscosity.

An observation of Fig. 3 shows that the viscometric curves are nearly at the similar values of viscosity across the shear rates probed, from the lowest temperature of 80°F up to approximately 178 to 180°F. This observation is consistent with the design of the spacer as highlighted elsewhere<sup>13</sup>. At the next higher temperature of 258 to 260°F, the viscosity data show a noticeable reduction in the viscosity values across the range of shear rates. Moreover, changes in temperature causing changes in inter-particle potentials could potentially alter the shape of the viscometric curve. However, from Fig. 3, it is apparent that the nature (shape) of the viscometric curve has remained almost identical across the temperature range probed (well within the limit of stability of the spacer material). This behavior is contrary to what would be expected for a system whose viscosity would be a function of the interactions between the various moieties in the system. Again, as observed in the previous section, from a field perspective, this lends an ease of extrapolation of behavior when moving across temperature ranges; but, from a scientific perspective, this would be unexpected. Efforts are underway to understand, in greater detail, how the interactions between particles and polymers play out dictating the overall viscosity of the spacer system (and indeed in cement and mud systems as well).

Two important conclusions of use to field applications can be drawn:

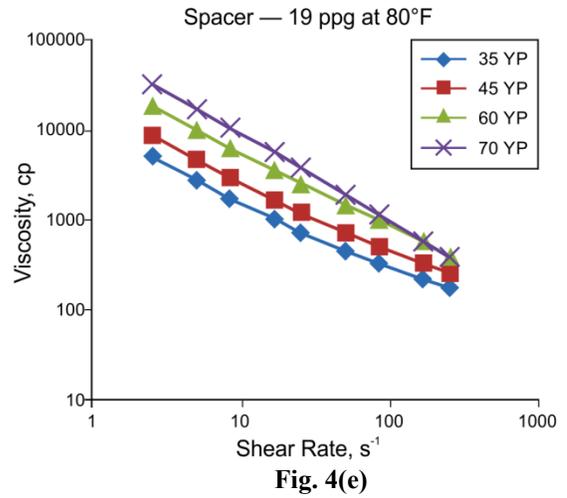
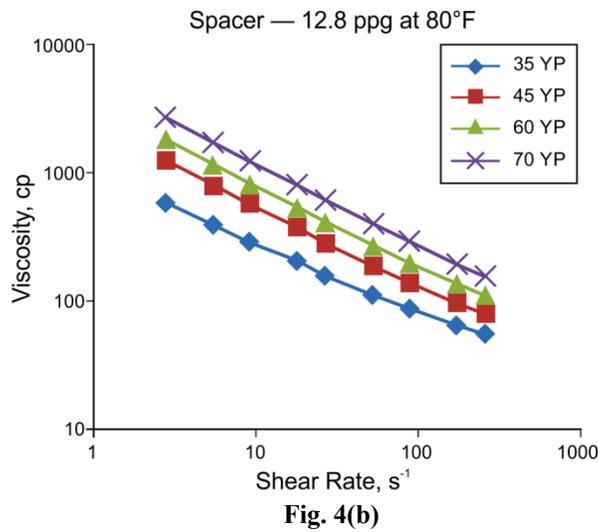
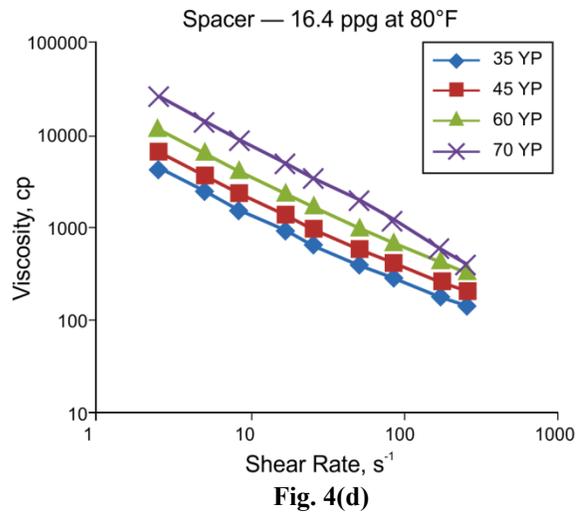
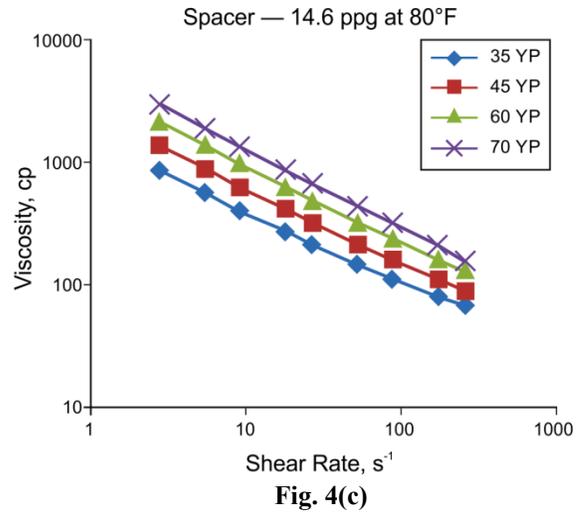
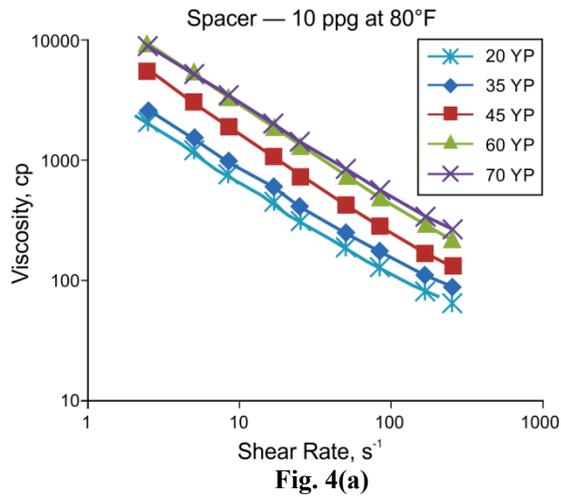
- As the temperature that the spacer encounters is increased, the viscometric data of the spacer remains fairly similar up to approximately 180°F; beyond which, it reduces.
- The nature of the viscometric curve (at constant density and pressure) remains unchanged across a wide range of temperatures relevant to field application of the spacer.

#### ***Effect of Density on YP Effects on Viscometric Data (Maintaining Temperature, and Pressure Constant)***

A variation in density of the spacer is caused by varying the ratios of the spacer material and barite in the dry blend. At a particle level, this entails changing the ratio (and hence volume fraction) of the individual particles and polymers in the dry blend. As a result, the net interaction potential between the various moieties would be expected to differ with varying densities. This would then be expected to change the shape of the viscometric curves with varying densities. Increasing density would certainly be expected to increase the viscosity of the spacer. Additionally, the expected change in the net interaction potential between the various constituents would be expected to change the shape of the viscometric curves as well.

Fig. 4 illustrates the effect of density on the YP-dependent viscometric curves. In the data shown, the temperature is maintained at a constant  $80 \pm 0.1^\circ\text{F}$ . Note that the pressure is maintained at  $500 \pm 20$  psi throughout the measurement. Several observations can be drawn by comparing Figs. 4(a) through (e):

- The increasing YP causes enhanced viscosities for all the densities probed within the range of 10 to 19 ppg. This enhanced viscosity is preserved across the range of shear rates tested.
- The viscometric curve for the 70 YP formulation exhibits some deviation from a straight line, at the higher shear rate region. This is particularly true for the spacer with the highest density of 19 ppg.
- The shape of the viscometric curve is maintained across the entire density range probed from 10 to 19 ppg.
- The change in viscosity across YPs is more uniform beyond the 10 ppg spacer. In other words, the increase in viscosity with increasing YP is more uniform (opposed to being marginal between 20 and 35 YP and between 60 and 70 YP) with the spacer of density 12.8, 14.6, 16.4, and 19 ppg.



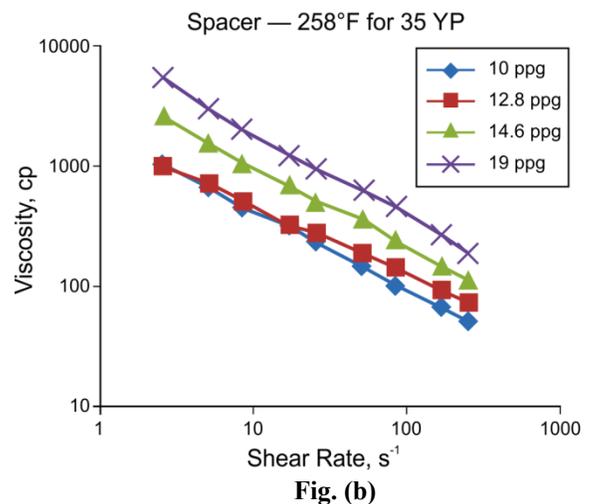
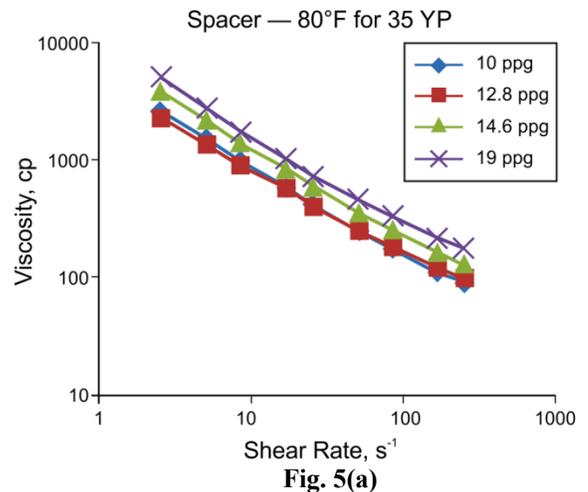
**Fig. 4—Effect of density on YP-dependent viscometric curves for spacer. The temperature is maintained at 80° ± 0.1°F, and the pressure is maintained at 500 ± 20 psi throughout the measurement.**

An observation of Fig. 4 shows that density does not appear to have a noticeable effect on the shape of the viscometric curve across the range of density probed—from 10 to 19 ppg. The slight anomaly in the high YP (70) data at the high shear rate region can be attributed to slip, which might be responsible for the abrupt reduction in viscosity at the high shear rate.

For the 20 YP spacer, the highest density it could sustain was determined to be 10 ppg. Higher density formulations indicated signatures of settling in the rheology, and hence, were not pursued.

As discussed previously, because of a change to the ratio of the individual particles and polymers in the spacer as a result of varying density, the shape of the viscometric curves can be expected to change as well. However, the test data indicate a similar shape of the viscometric curves across all the densities probed and across all YPs (with the exception of slip at the high YP and high shear rate range). Again, as previously discussed, further definitive testing is underway to probe more into the nature of the interactions between the various moieties in the spacer to better understand the consequences on viscosity in a wide range of suspension systems, extending to cement and mud. However, from a field perspective, this maintenance of similar shapes of viscometric curves lends an ease of extrapolation of field behavior when moving across densities and to saving time during laboratory testing.

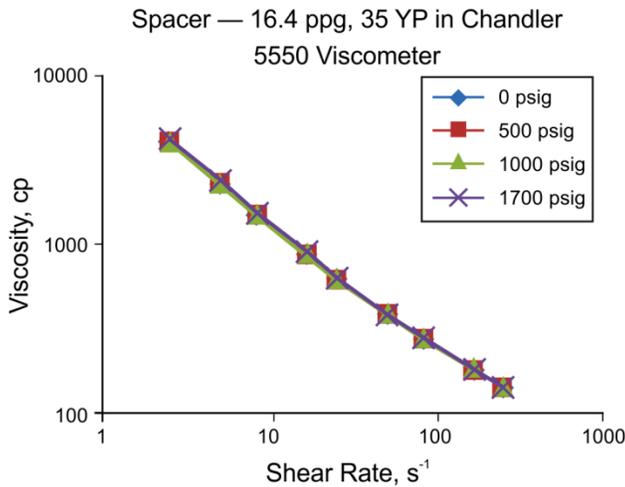
To further ascertain the similarity of the viscometric curves across densities and temperatures, Fig. 5 shows the viscometric curves at the low temperature of 80°F (Fig. 5(a)) and at the high temperature of 258°F (Fig. 5(b)). The YP is held constant at an arbitrarily chosen value of 35, but the data are representative of the other YP data. The data in Fig. 5(a) is a close-up view of the data presented in Fig. 4, focusing on the chosen YP of 35 lb<sub>f</sub>/100 ft<sup>2</sup>, to closely observe the effect of density on the viscometric curves and maintain all other variables of the YP, temperature, and pressure constant. The data in Fig. 5(b) is an extension of the data in Fig. 4 showing similar data for the high temperature of 258°F. It is thus clear that the shape of the viscometric curves is similar across all densities, YPs, and temperatures probed.



**Fig. 5—Effect of density on viscometric curves for the spacer of 35 YP. The temperature is maintained at 80° ± 0.1°F for Fig. 5(a), 258° ± 0.1°F for Fig. 5(b), and the pressure is maintained at 500 ± 20 psi throughout the measurement.**

#### ***Effect of Pressure on Viscometric Data (Maintaining YP, Temperature, and Pressure Constant)***

Fig. 6 illustrates the effects of pressure up from 0 to 1,700 psig for the spacer with 16.4 ppg density and a YP of 35. It is evident from Fig. 6 and Table 1 that pressure does not impact rheology for this pressure range. Work is underway to measure the impact of pressure for pressures up to 30,000 psig.



**Fig. 6—Effect of pressure on viscometric curves for spacer of 16.4 ppg density and 35 YP. The temperature was maintained at 80° ± 0.1°F throughout the measurement.**

**Table 1—Effect of pressure on viscometric curves for spacer of 16.4 ppg density and 35 YP. The temperature was maintained at 80° ± 0.1°F throughout the measurement. Data were best fit for the Herschel-Bulkley rheological model.**

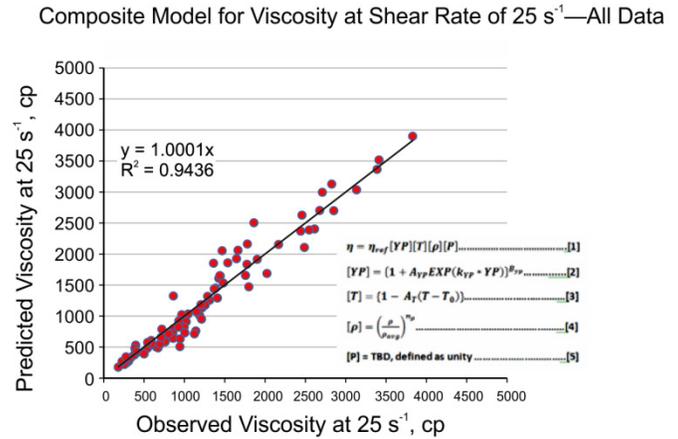
Pressure (psig)	YP (lb <sub>p</sub> /100ft <sup>2</sup> )	Apparent Viscosity (PV) (cP)	Power Law Exponent (n)	R <sup>2</sup>
0 ± 6	31.0	80.0	0.57	0.9994
500 ± 32	31.1	78.1	0.57	0.9991
1000 ± 39	30.6	79.8	0.58	0.9992
1700 ± 31	32.9	78.3	0.58	0.9992

**Composite Rheological Model**

All data collected during this study for temperatures from 80 to 260 °F were best fit to Eq. 1. It is important to note that the spacer physico-chemistry used during this study was designed for temperatures < 270°F, thus the few tests that were conducted at 278 and 298 °F were excluded because of various points of thermal instability. Fig. 7 illustrates a summary plot of observed viscosities at a shear rate of 25 (sec<sup>-1</sup>) plotted against the Eq. 1 predicted values. The best fit values for the parameters in Eqs. 2 through 6 are listed as follows:

$$\begin{aligned} \tau_{0,ref} &= 7.9 \text{ lbf/ft}^2 \text{ or } 3.8 \text{ Pa-sec} \\ K_{hb,ref} &= 1.03 \text{ Pa-sec}^n \\ n_{hb} &= 0.44 \\ A_{yp} &= 0.079 \\ K_{yp} &= 0.10 \\ B_{yp} &= 0.50 \\ A_T &= 0.0020 \\ T_0 &= 80 \text{ }^\circ\text{F} \\ n_p &= 1.0 \\ \rho_{avg} &= 14.5 \text{ ppg} \end{aligned}$$

It should be noted that  $\rho_{avg}$  is the average of all the densities evaluated during this study.



**Fig. 7—Eq. 1 through 6 best fit to all test data that were < 260 °F.**

**Conclusions**

The viscosity model of Eq. 1 helps predict a wide range of viscosities within a broad range of spacer parameters. The dimensionless parameter module format aids with understanding the impact of each variable and developing a model with rational boundary limits.

This particular spacer type maintains similar linear shear thinning nature within a wide range of YPs, densities, and temperatures.

The rate of thermal thinning begins to change between 178 and 258°F, which is expected provided that the upper design temperature of this system is approximately 270°F.

Effects of the targeted YP on the spacer design exponentially impact viscosity.

Pressure had no appreciable impact on the rheology from up to 1,700 psig. It is important to continue this study for pressures approaching 30,000 psig.

**Acknowledgments**

The authors thank Halliburton for permission to present this research.

**References**

1. Becker, T.E., Morgan, R.G., Chin, W.C., and Griffith, J.E. 2003. Improved Rheology Model and Hydraulics Analysis for Tomorrow’s Wellbore Fluid Applications. Paper SPE 82415 presented at the SPE Production and Operations Symposium, Oklahoma City, Oklahoma, USA, 22–25 March.
2. Okumo, I. and Isehunwa, S.O. 2007. Prediction of the Viscosity of a Water-Base Mud Treated With Cassava Starch and Potash at Varying Temperatures Using Factorial Design. Paper SPE 111886 presented at the 31<sup>st</sup> Nigerian Annual International Conference and Exhibition, Abuja, Nigeria, 6–8 August.
3. Barrufet, M.A. and Setiadarma, A. 2003. Experimental

Viscosities of Heavy Oil Mixtures up to 450 K and High Pressures using a Mercury Capillary Viscometer. *Journal of Petroleum Science and Engineering*. **40** (1–2): 17–26.

4. Amani, M. and Hassiba, K.J. 2012. Salinity Effect on the Rheological Properties of Water Based Mud under High Pressures and High Temperatures of Deep Wells. Paper SPE 163315 presented at the Kuwait International Petroleum Conference and Exhibition, Kuwait City, Kuwait, 10–12 December.
5. Olowolagba, K. and Yerubandi, K.B. 2011. Improved Spacer Rheology Model for Cement Operations. Paper SPE 140805 presented at the Production and Operations Symposium, Oklahoma City, Oklahoma, USA, 27–29 March.
6. Agarwal, S., Walker, L.M., Prieve, D.C., Soong, Y., and Gupta, R.K. 2009. Using Nanoparticles and Nanofluids to Tailor Transport Properties of Drilling Fluids for HTHP Operations. Paper AADE-2009-NTCE-18-05 presented at the AADE National Technical Conference and Exhibition, New Orleans, Louisiana, USA.
7. Ibeh, C., Schubert, J., Teodoriu, C., Gusler, W., and Harvey, F. 2008. Investigation on the Effects of Ultra-High Pressure and Temperature on the Rheological Properties of Oil-Based Drilling Fluids. Paper AADE-08-DF-HO-13 presented at the AADE Fluids Conference and Exhibition, Houston, Texas, USA, April 8–9.
8. Ibeh, C., Schubert, J., and Teodoriu, C. 2008. Methodology for Testing Drilling Fluids under Extreme HP/HT Conditions. Paper AADE-08-DF-HO-14 presented at the AADE Fluids Conference and Exhibition, Houston, Texas, USA April 8–9.
9. Walters, H.G. Morgan, R.G., and Harris, P.C. Kinetic Rheology of Hydraulic Fracturing Fluids. 2001. Paper SPE 71660 presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, September 30–October 3.
10. API Recommended Practice 10B-2, Recommended Practice for Testing Well Cements, 2<sup>nd</sup> edition, American Petroleum Institute, (2013)
11. Williams, D.A., Saak, A.W., and Jennings, H.M. 1999. The Influence of Mixing on the Rheology of Fresh Cement Paste. *Cement and Concrete Research*. **29** (9): 1491–1496.
12. Maxey, J. 2007. Thixotropy and Yield Stress Behavior in Drilling Fluids. Paper AADE-07-NTCE-37 presented at the AADE National Technical Conference and Exhibition, Houston, Texas, USA, April 10–12.
13. Gordon, C., Lewis, S., and Tonmukayakul, P. 2008. Rheological Properties of Cement Spacer: Mixture Effects. Paper AADE-08-DF-HO-09 presented at the AADE Fluids Conference and Exhibition, Houston, Texas, USA, April 8–9.

$A_{YP}$  = YP coefficient

$k_{YP}$  = YP exp coefficient

$B_{yp}$  = YP exponent

$A_T$  = Temperature coefficient for thermal thinning

$T_0$  = Reference Temperature of 79°F (°F)

$n_\rho$  = Density exponent

$n_{hb}$  = HB shear thinning index at ref. conditions

$T$  = Temperature (°F)

## Nomenclature

$\rho$  = Density in (lb<sub>m</sub>/gal or ppg)

$\rho_{avg}$  = Average of all densities tested (lb<sub>m</sub>/gal or ppg)

$\dot{\gamma}$  = Viscometric shear rate (sec<sup>-1</sup>)

$\eta_{ref}$  = Apparent viscosity at reference conditions:  $\rho = 10$  ppg; YP = 10 lb<sub>f</sub>/100 ft<sup>2</sup>, T = 80°F, and P = 500 psig.

$\tau_{0,ref}$  = Herschel-Bulkley (HB) yield stress at ref. conditions

$K_{hb,ref}$  = HB consistency coefficient at ref. conditions