

Real-Time Friction Factor Monitoring: Characterization of Drag Reduction in Polymer-Based Fluids

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* Now with QRI; **now with GE Baker Hughes

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Abstract

Sophisticated new drilling technologies such as managed pressure drilling (MPD) and dual gradient drilling (DGD) rely critically on accurate hydraulics modeling, demanding more precise and more frequent predictions of pump pressures, bottom-hole and annular pressures than are provided by current fluid measurement and characterization technology. This paper shows how fluid rheological behavior can be more accurately monitored for better hydraulics modeling and control using real-time automated rheology measurement.

A series of experiments was performed using a fully automated high temperature pipe viscometer in order to understand the effects of long chain polymer-based additives commonly used in drilling, completions, and well intervention operations on fluid behavior in laminar, transitional and turbulent flow. Frictional pressure losses were measured in a cesium formate fluid viscosified with concentrations of xanthan gum up to 2.5 lb/bbl at temperatures ranging from 100 – 230°F. Results were compared with widely used theoretical models for frictional pressure losses, showing significant discrepancy between current theory and empirical results.

First, contrary to expectations, the polymers were observed to shift their role from viscosifier in the laminar range to friction/drag reducer in the transitional and turbulent ranges. Secondly, increasing temperature has a non-trivial effect on pressure loss measurements. Thirdly, shear degradation effects on the polymer need to be accounted for, particularly in fully developed turbulent flow. Results of this study show the necessity for more accurate and more frequent real-time drilling fluid characterization at field locations, a challenge addressed by a recently introduced automated pipe viscometer concept.

Introduction

Most fluids used to drill, cement and complete present-day oil/gas wells exhibit non-Newtonian, shear-thinning behavior. Prediction of frictional pressure losses plays a vital role in modeling the hydraulics of such non-Newtonian fluids. This is particularly important when encountering a narrow mud window (i.e. the difference between the fracture gradient and either the pore pressure or the mud weight required for borehole stability, whichever of the two is greater), such as in deepwater wells, and/or dealing with high frictional pressures within the available window, such as on extended reach (ERD) and slim-

hole wells. Exceeding the boundaries of the mud window usually results in significant drilling problems (e.g., well control incidents, lost circulation, borehole instability, stuck pipe, etc.) and associated non-productive time and recovery costs (see e.g. Karimi Vajargah and van Oort, 2015; Subramanian and Azar, 2000). Precise prediction of pressure losses is therefore crucial to properly manage bottom-hole pressures within the available mud window, especially if advanced drilling technologies such as MPD and DGD are necessary to help manage such pressures within the available margin.

Well-established and relatively accurate analytical methods are available to predict the frictional pressure losses of Newtonian fluids in both laminar and turbulent flow. However, the development of such methods is very cumbersome for non-Newtonian fluids due to their complex rheological behavior. Well-established analytical methods exist for laminar flow of some non-Newtonian fluids, but for turbulent flow the models introduced so far are not yet reliable (Chilton and Stainsby, 1998).

Several factors, such as rheological complexity of the fluid and turbulent eddies, make mathematical modeling of turbulent flow of non-Newtonian fluids complicated. To overcome this complexity, an empirical friction factor term is usually introduced. Several correlations have been proposed to obtain the friction factor for turbulent flow of Newtonian fluids in pipes (e.g. Colebrook, 1939; Blasius 1913). These equations present acceptable accuracy for a variety of practical applications; however, only a few robust experimental studies have been carried out for non-Newtonian fluids. In addition, transitional flow is encountered in drilling applications, and there is currently no well-established model to calculate the friction factors for non-Newtonian fluids in this flow regime.

Dodge and Metzner (1959) proposed a semi-empirical friction factor correlation for turbulent flow of non-Newtonian, time-independent, non-elastic fluids in smooth pipes. As will be discussed below, this correlation exhibits acceptable accuracy for some non-Newtonian fluids and hence is extensively used in the drilling and well completion industry. However, the use of certain additives in these fluids makes this correlation unreliable. For instance, long-chain polymer additives are extensively used in drilling and completion fluids as viscosifiers and fluid loss agents. Their presence in these fluids

may delay the transition from laminar to turbulent flow. Knowledge of the critical Reynolds number characterizing this transition is very important in hydraulic planning and cuttings transport optimization. In addition, due to inherent friction reduction qualities of polymers, the pressure loss in turbulent flow observed for polymeric fluids can be significantly less than predicted (e.g., Subramanian and Azar, 2000; Graham, 2004; Dosunmu and Shah, 2013; Karimi Vajargah et al., 2016). This can lead to significant overestimation of pump pressure and equivalent circulation density (ECD) in the transitional/turbulent flow regime.

In this study, we investigate the effects of drilling fluid composition on frictional pressure losses in more detail. Several types of drilling fluids are tested and results are compared to widely used hydraulic models. A new method of predicting frictional pressure losses, enabled by the extensive experimental data generated in this study, is also proposed and evaluated.

Background

Dodge and Metzner (1959) developed a semi-empirical equation for friction factor in fully developed turbulent flow of time-independent, purely viscous non-Newtonian fluids in smooth pipes. They applied Prandtl's mixing length theory, obtaining suitable values for the empirical constants from the experimental data. The Dodge and Metzner correlation has been widely accepted and is routinely quoted in books on non-Newtonian fluid technology (e.g. Chabra and Richardson, 1999; Skelland, 1967; Steffe, 1996; Ahmed and Miska, 2009). Similar to the Dodge and Metzner equation, several other friction factor correlations have been introduced for pipe flow of power law fluids (e.g., Tomita, 1959; Clapp, 1961; Trinh, 1969; Shah, 1984; Desouky, and El-Emam, 1990; El-Emam et al., 2003).

Torrance (1963) extended Dodge and Metzner's work to be applicable to yield pseudo-plastics and to account for pipe roughness. Only a few correlations addressing relative roughness for non-Newtonian fluids can be found in literature (Szilas et al., 1981; Shah, 1990; Reed and Pilehvari, 1993).

As a common practice for non-Newtonian well construction fluids, the end of stable laminar flow is considered to occur when the Reynolds number is approximately 2100 (Ahmed and Miska, 2009). Although this is a reasonable assumption for several drilling fluids, it cannot be generalized for all types of non-Newtonian fluids. For these, the critical Reynolds number is not constant, but is a function of generalized flow behavior index (Dodge and Metzner, 1959; Kelessidis et al., 2011).

It is also possible to predict the transition from laminar to non-laminar flow based on stability analysis. Ryan and Johnson (1959) developed a stability criterion based on the ratio of input energy to energy dissipation for an element fluid volume that depends on local parameters. Several other transition criteria have been proposed to predict the critical Reynolds number (e.g., Mishra and Tripathi, 1971; Hanks and Ricks, 1974; Desouky 1991; Merlo, et al., 1995; Slatter, 1999; Kalayci et al., 2013).

Experimental Setup High Temperature Flow Loop

Experimental data for this study was collected using a dedicated flow loop system. This system includes a fluid reservoir, heating system, positive displacement pump, flow meter, two horizontal insulated pipe sections of different diameters, and differential pressure transducers to measure frictional pressure losses inside the straight pipe sections. The loop is 5.5 m (18 ft) long and is composed of two different pipe sections, 1.27 cm (0.5 in) and 0.9525 cm (0.375 in) in diameter. Wall thickness for both pipes is 0.89 mm (0.035 in). An automated heating system and insulation were installed in the mud tank to heat the drilling fluids up to 230°F. A thermostat attached to a thermocouple installed in the reservoir enables closed-loop temperature control, providing the capability to maintain temperatures within a window of approximately +/- 2°F while the system is in operation. Two differential pressure transducers are used in the test section to obtain the pressure loss data, with pressure taps separated by 3.048 m (10 ft) on both pipes. Entrance and exit effects were estimated based on empirical correlations from literature (Collins and Schowalter, 1963) in order to minimize flow anomalies. **Figs. 1a** and **b** show the flow loop and related schematics.

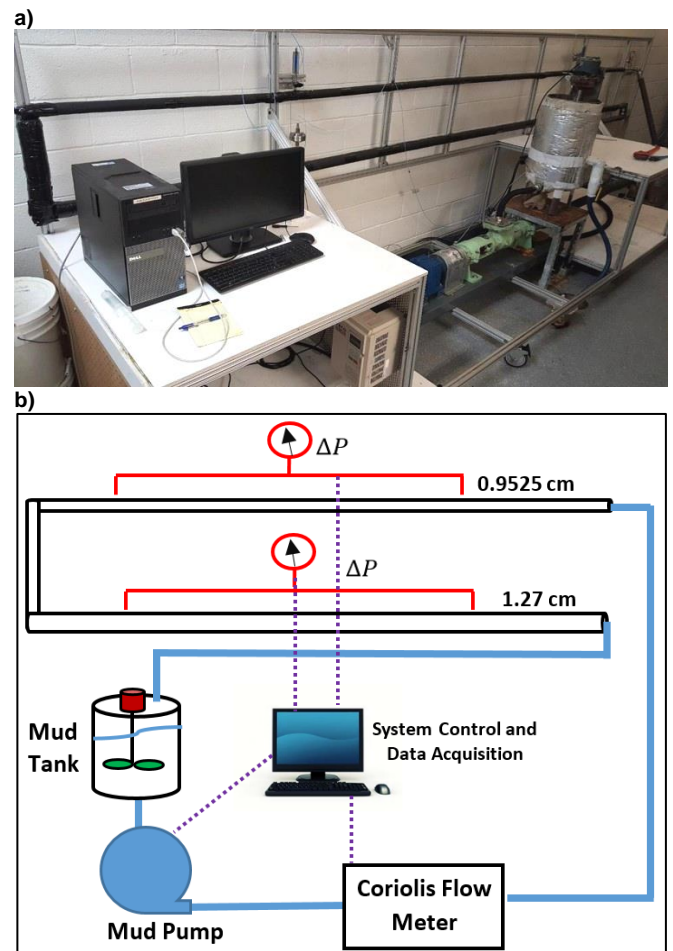


Figure 1: (a) Image of flow loop (b) Related schematics.

A progressive cavity pump was used to circulate fluid with the inlet located at the bottom of a 40 liter (10.57 gallon) reservoir. Fluid density, temperature and flow rate were measured using a Coriolis flow meter. Data was recorded using a fully automated control and data acquisition system, which monitored flow rate, differential pressure, density and temperature. Experiments were conducted at three standardized temperatures: 100°F, 150°F and 230°F. These values provided consistent test data without exceeding equipment limitations.

Calibration Test with Newtonian Fluids

After calibration of the pressure sensors, water was tested in the experimental setup to validate the accuracy of the data collected. **Figure 2** compares the experimental values with Colebrook's (1939) correlation, showing excellent agreement between experimental and theoretical values.

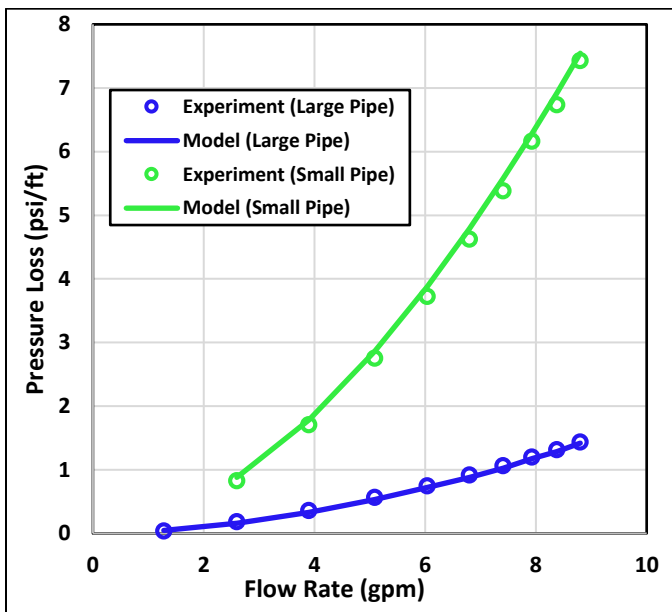


Figure 2: Validation test with water for both test pipes. Excellent agreement between the experimental and theoretically predicted values was observed.

Fluids Tested

A total of 6 fluids were tested in this study. The base fluid consisted of saturated cesium formate brine viscosified with xanthan gum in increments of 0.5 lb/bbl ranging from 0.0 to 2.5 lb/bbl. The fluids tested are shear-thinning and thixotropic, and therefore when left static for a period of time will build up a significant but fragile gel structure. It was imperative before performing experiments to circulate the fluid in the flow loop at low temperatures in turbulent flow until the frictional pressure drop readings became stable. A rotational viscometer was used to obtain the rheological parameters in accordance with a yield-power-law (YPL) rheological model. Table 1 presents rheological parameters for each fluid.

Table 1: YPL rheological properties (yield stress, τ_y , consistency index, K , flow behavior index, m) and density for each fluid at 100°F.

Polymer Concentration (lb/bbl)	Specific Gravity	K ($\text{Pa}\cdot\text{s}^m$)	m	τ_y (Pa)
0.00	2.13	0.00	1.00	0.12
0.50	2.25	0.11	0.68	0.17
1.00	2.22	0.50	0.50	0.80
1.50	2.20	0.70	0.52	2.44
2.00	2.18	1.03	0.48	3.94
2.50	2.17	1.38	0.46	5.85

Modeling

Two approaches for pressure loss prediction are used here. The first applies the widely used Dodge and Metzner (1959) equation to predict the friction factor, while the second approach uses real-time friction factor data by applying curve fitting techniques.

Industry Method

Prediction of frictional pressure losses requires the determination of a friction factor f for a given set of flow parameters. This friction factor is utilized in Equation 1 to calculate frictional pressure losses in any given pipe section.

$$\frac{dp}{dl} = \frac{2f\rho V^2}{D} \quad (1)$$

where V is the average fluid velocity, ρ is the fluid density, and D is the inner diameter of the pipe. For laminar flow of YPL fluids, the friction factor is determined by first calculating the shear stress at the wall, τ_w , using Equation 2.

$$\frac{8V}{D} = \frac{(\tau_w - \tau_y)^{\frac{1+m}{m}}}{K^{\frac{1}{m}} \tau_w^3} \left(\frac{4m}{3m+1} \right) \left[\tau_w^2 + \frac{2m\tau_y\tau_w}{1+2m} + \frac{2m^2\tau_y^2}{(1+m)(1+2m)} \right] \quad (2)$$

where v is the fluid velocity, τ_y is the yield stress, K is the consistency index, and m is the fluid behavior index of the fluid being analyzed.

Once τ_w has been calculated using Equation 2 it can be used in Equation 3 to calculate the Reynolds number.

$$Re = \frac{8\rho V^2}{\tau_w} \quad (3)$$

The Reynolds number can then be utilized in Equation 4 to find the Fanning friction factor f for laminar flow.

$$f = \frac{16}{Re} \quad (4)$$

For turbulent flow, the correlation for non-Newtonian fluids developed by Dodge and Metzner (1959) provides a robust method for calculation of the friction factor. This correlation is represented below by Equation 5.

$$\frac{1}{\sqrt{f}} = \frac{4}{N^{0.75}} \log \left(Re \times f^{\left(1 - \frac{N}{2}\right)} \right) - \frac{0.4}{N^{1.2}} \quad (5)$$

where Re is the Reynolds number, f is the Fanning friction factor and N is the generalized flow behavior index found in Equation 6.

$$\frac{1}{N} = A + B$$

$$A = \frac{(1-2m)\tau_w + 3m\tau_y}{m(\tau_w - \tau_y)} \quad (6)$$

$$B = \frac{2m(1+m)[(1+2m)\tau_w^2 + m\tau_y\tau_w]}{m(1+m)(1+2m)\tau_w^2 + 2m^2(1+m)\tau_w\tau_y + 2m^3\tau_y^2}$$

Equations 7 and 8 are used to determine whether flow is laminar or turbulent.

$$Re_1 = 3250 - 1150N \quad (7)$$

$$Re_2 = 4150 - 1150N \quad (8)$$

If the Reynolds number from Equation 3 is less than Re_1 , the flow is assumed to be laminar and Equation 4 is used to predict the friction factor. If it is greater than Re_2 , it is assumed to be turbulent and Equation 5 is used to predict the friction factor. Between these two thresholds a transition region exists where the friction factor is calculated by interpolating between the values calculated for fully laminar and fully turbulent flow. Once the friction factor is known, it is utilized in equation 1 to predict frictional pressure losses.

Real-time Measurement

A second approach presented here relies on automated real-time measurement of the friction factor. This procedure requires pressure vs. flow rate data and rheological parameters for the fluid under investigation. This data can be collected by a system similar to the experimental setup used in this study, with a pump, flow meter, and a section of straight pipe fitted with differential pressure transducers.

Karimi Vajargah et. al. (2016) presented and demonstrated the viability of a method for using this system to determine the rheological parameters of drilling fluids. This technology, which uses a pipe or capillary viscometer, has long been utilized for other applications such as food processing and enhanced oil recovery (Suzuki, 1994; Liauh and Liu, 1984). Ahmed and Miska (2009) state that pipe viscometers often provide more accurate rheological measurements than rotational viscometers.

Once the rheological parameters of the fluid have been determined and pressure vs. flow rate measurements have been obtained, the process for real-time determination of friction factor begins with the creation of a plot of friction factor vs. Reynolds number. Equation 2 is used to find the theoretical laminar values for τ_w for the given fluid velocity, and the corresponding Reynolds number is calculated with Equation 3. Rearranging Equation 1 to solve for f allows the friction factor to be determined for each data point.

Once the friction factor vs. Reynolds number plot is generated for a particular fluid, a curve is fitted to the data and used to predict the friction factor at any Reynolds number within the domain of the data set.

Results and Discussion

Theoretical Model Validation

Two muds were tested by Karimi Vajargah et. al. (2017) and results compared to predictions from the established model to validate the model's accuracy for generic drilling fluids. Mud

A, a bentonite clay mud, showed very good agreement with the model in both laminar and turbulent flow. Figure 3 shows frictional pressure loss vs. flow rate for mud A.

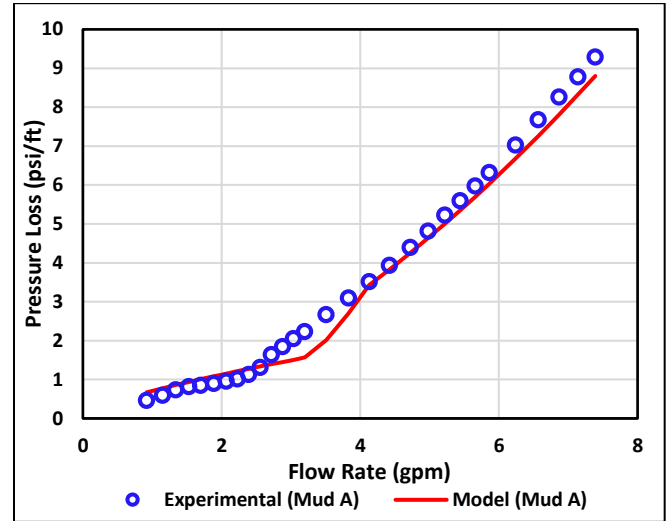


Figure 3: Comparison between values obtained from the experimental data and the model for Mud A (bentonite clay mud).

A synthetic-based field mud B also showed very good agreement between the experimental results and model predictions. Figure 4 shows frictional pressure loss vs. flow rate for mud B. Although the shape of the curve is noticeably different from the curve for mud A (Figure 3), the model still predicts pressure losses with a high degree of accuracy in both laminar and turbulent flow. These two tests demonstrate that the model provides accurate results for two substantially different fluids.

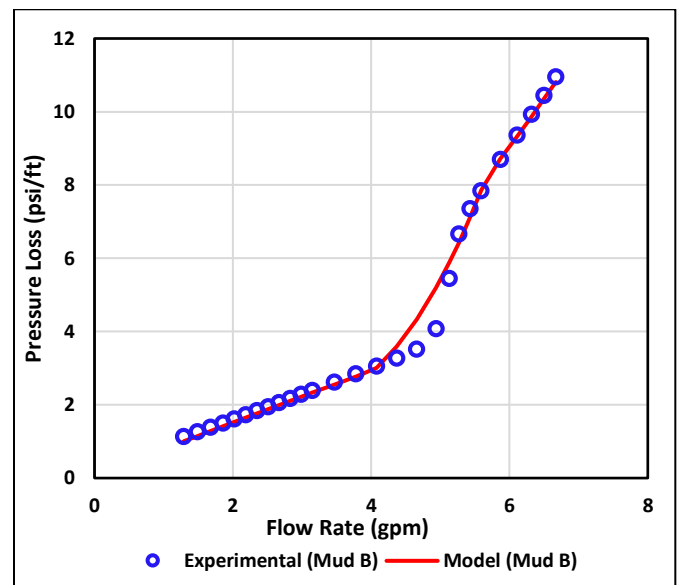


Figure 4: Comparison between values obtained from the experimental data and the model for Mud B (synthetic-based mud).

Effect of Polymer Concentration on Frictional Pressure Loss

Karimi Vajargah et. al. (2017) discussed anomalies in pressure loss predictions for high polymer content fluids. To further investigate these anomalies, this work presents a more comprehensive polymer concentration study using xanthan gum. Cesium formate brine was used as the base fluid for this study and tests were performed with xanthan additive concentrations from 0 to 2.5 lb/bbl. Pressure loss vs. flow rate data from all concentrations tested at 100°F are shown in **Figure 5**.

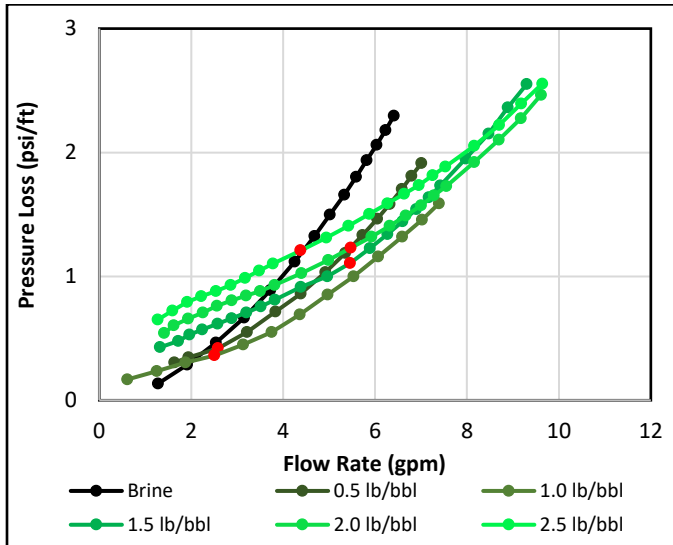


Figure 5: Experimental data from cesium formate brine in a 1/2" tube at 100°F with xanthan concentrations from 0 to 2.5 lb/bbl. Red dots represent the last laminar data point before the flow begins to transition to turbulence. Results show contrasting polymer behavior in laminar and turbulent flow.

To assist in the interpretation of these results, red dots mark the data points where turbulent flow is predicted to begin for each fluid. This transition point was estimated by creating a plot of friction factor vs. flow rate as shown in **Figure 6**. A straight line was added to this figure following the slope of the laminar flow region. The first data point deviating from this trend was assumed to indicate a transition to turbulence.

Figure 5 shows an intriguing contrast between the laminar and turbulent flow regime. In laminar flow, higher xanthan concentrations resulted in increased frictional pressure losses, with the highest polymer content fluid showing frictional pressure losses greater than 3x those of the base brine at 1.3 gpm.

In turbulent flow, however, the trend reversed. By the time flow reached 5 gpm, the brine had the highest frictional pressure loss of all fluids tested, and the disparity continued to grow at higher flow rates. Although equipment limitations prevented testing lower xanthan concentrations at flow rates up to 10 gpm, the slope of the curves shows a strong likelihood that the order of data series on the graph would completely invert (i.e. highest xanthan concentrations exhibiting lowest frictional pressure loss) at higher flow rates.

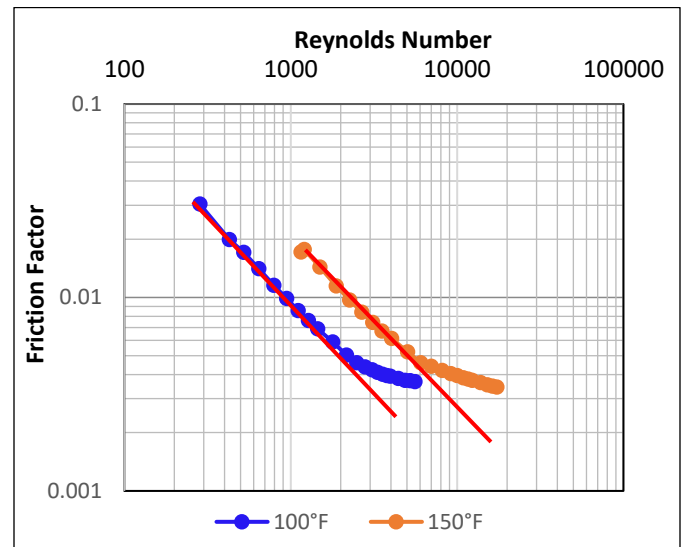


Figure 6: Chart of friction factor vs. Reynolds number for cesium formate brine containing 1.5 lb/bbl xanthan at two temperatures. The red line was assumed to represent the laminar portion of the test data.

Tests conducted at 150°F show that this inversion does indeed occur at higher Reynolds numbers. **Figure 7** shows pressure loss vs. flow rate for all polymer concentrations tested at 150°F in the 1/2" OD tube. Trends in the data series appear similar to those observed at 100°F, but with an earlier inversion point between the laminar and turbulent pressure trends. This result is to be expected due to the decreased viscosity of all fluids at increased temperature, causing the flow to transition to turbulence at lower flow rates.

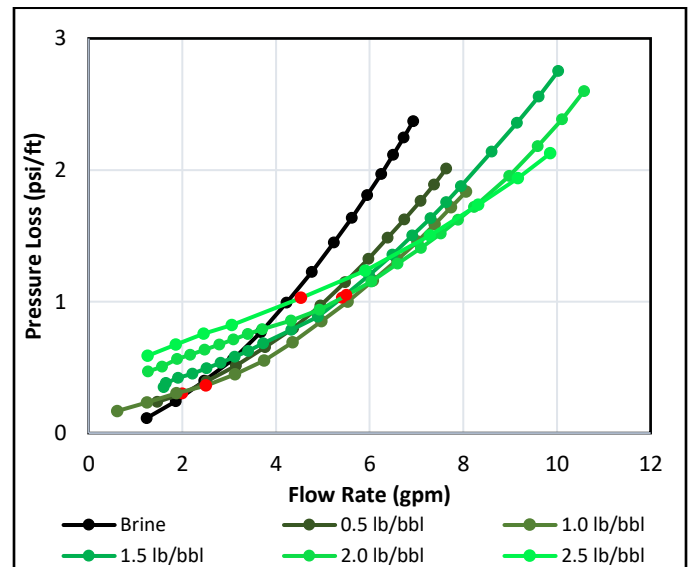


Figure 7: Experimental data from cesium formate brine in a 1/2" OD tube at 150°F with xanthan concentrations from 0 to 2.5 lb/bbl. Red dots represent the last laminar data point before the flow begins to transition to turbulence.

Flow in the 3/8" tube at 150°F is turbulent for almost the entire range of flow rates and Xanthan concentrations tested.

Graphing the friction factor vs. Reynolds number allows for a more thorough examination of the turbulent pressure trend, which shows a decreasing friction factor with increasing xanthan concentration. **Figure 8** shows friction factor vs. Reynolds numbers for all fluid concentrations at 150°F in the 3/8" OD tube. Note that the gap in friction factor between the brine (no xanthan) and the fluid with 0.5 lb/bbl xanthan is significantly larger than the gaps between the fluids of higher polymer concentrations. Each 0.5 lb/bbl increase in polymer concentration led to a successively smaller reduction in pressure loss, implying that the drag reducing effect of further xanthan additions diminishes beyond a certain point.

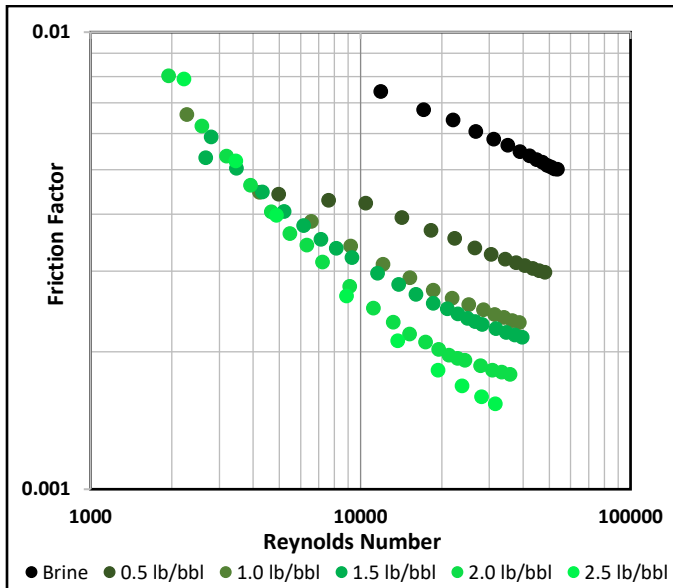


Figure 8: Experimental data from cesium formate brine in a 3/8" OD tube at 150°F with xanthan concentrations from 0 to 2.5 lb/bbl.

At 230°F, the highest temperature tested in this study, the inversion in trends between the laminar and turbulent flow regimes occurred at even lower flow rates than in the 150°F test. **Figure 9** shows pressure loss vs. flow rate for all polymer concentrations tested at 230°F in the 1/2" OD tube. The pressure readings taken from different polymer concentrations at this temperature are closer together than those from the tests conducted at 100 and 150°F, suggesting that increasing fluid temperature reduces the effect that polymer concentration has on the magnitude of frictional pressure losses.

In aggregate, results from this study highlight the complexity of polymer additive behavior. Observed frictional pressure losses showed significant variation according to several factors including concentration, temperature, flow rate, and flow regime. Considering xanthan gum's common use as a thickening agent in drilling and completion fluids, and the similarities in molecular structure between xanthan gum and many friction reducers, there appear to be commonalities in polymer additive behaviors regardless of the chemical's classification as a friction reducer or viscosifier.

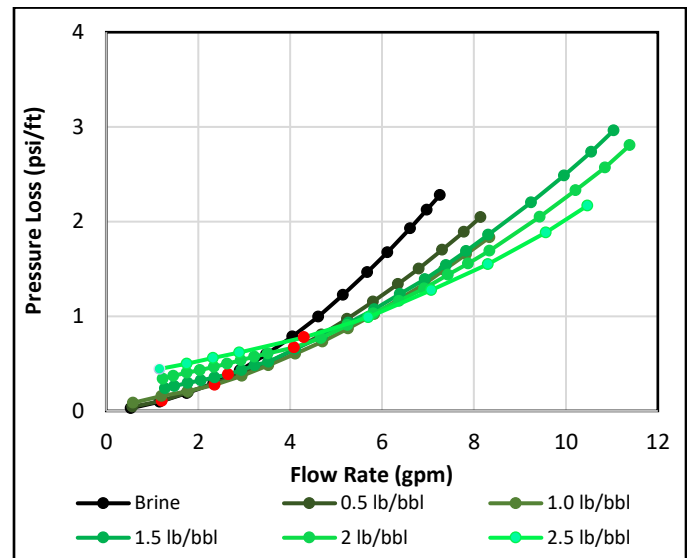


Figure 9: Experimental data from cesium formate brine in a 1/2" OD tube at 230°F with xanthan concentrations from 0 to 2.5 lb/bbl. Red dots represent the last laminar data point before the flow begins to transition to turbulence.

Effect of Polymer Concentration on Model Accuracy

The preceding section provides valuable insight into the complexity of overall trends in polymer behavior. However, this complexity is not inherently problematic for well construction applications unless it prevents accurate ECD prediction. To investigate this possibility, the data from these experiments was used to evaluate the effect of xanthan concentration on the accuracy of the previously described analytical modeling technique.

Rheological parameters for the fluids tested were used to predict the frictional pressure loss for each test performed in this study, utilizing the industry model previously described in this work. **Figure 10** compares model predictions with experimental data from the lowest xanthan concentration tested, 0.25 lb/bbl. Flow rates from 1.08 to 7.21 gpm were achieved during this test and Reynolds numbers ranged from 3110 to 30,400, implying that the flow was turbulent for the duration of the experiment. Excellent agreement was observed between predicted and experimental values.

Figure 11 shows predicted and measured pressure loss vs. flow rate for a xanthan concentration of 1.0 lb/bbl. Reynolds numbers ranged between 310 and 16,060 during this test. Agreement between the model and the experimental values remains very good within the laminar flow regime, with an error of approximately 4% at the highest laminar flow rate. In turbulent flow, however, a noticeable discrepancy emerges between the two trends. A 17% error in the model prediction was observed at the highest flow rate observed in this test, 8.06 gpm (which corresponds to a Reynolds number of 16,060).

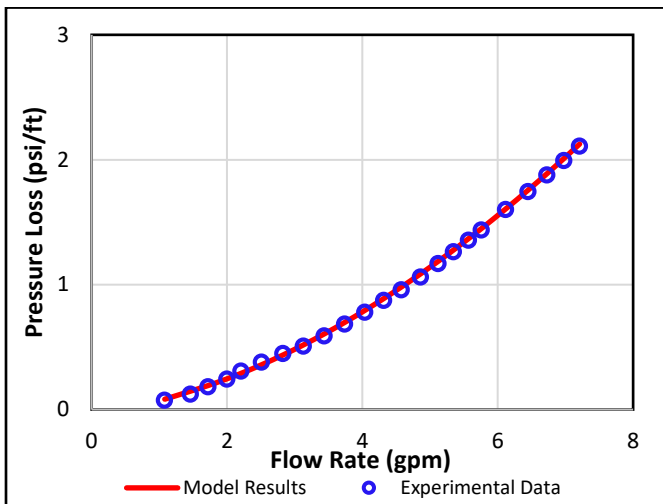


Figure 10: Comparison between experimental data and model for cesium formate brine containing 0.25 lb/bbl xanthan at 150°F.

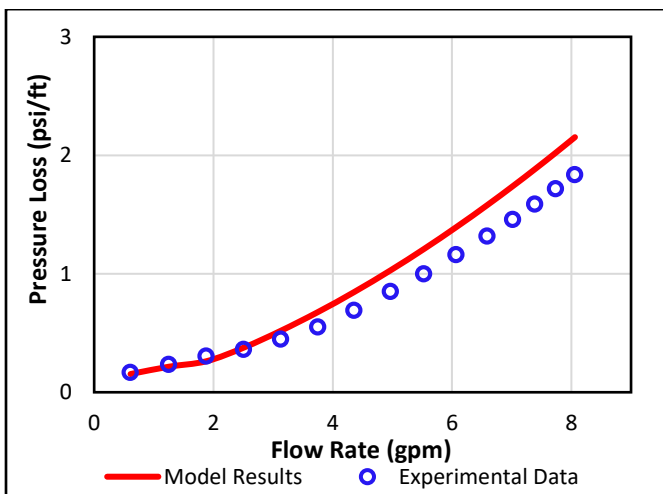


Figure 11: Comparison between experimental data and model for cesium formate brine containing 1.0 lb/bbl xanthan at 150°F.

Figure 12 shows predicted and measured pressure loss vs. flow rate for a xanthan concentration of 2.0 lb/bbl. Flow rates from 1.27 to 10.58 gpm were achieved during this test and Reynolds numbers ranged from 570 to 14,760. In turbulent flow a major discrepancy was observed between the model and the experimental results, with prediction error reaching 42% at 10.6 gpm (corresponding to a Reynolds number of 14,760). Agreement between the model and experimental results diminished in the laminar flow regime as well, but to a lesser degree than in turbulent flow. Error in model predictions reached 23% at the highest laminar flow rate.

The preceding data provide experimental evidence that current modeling methods struggle to accurately predict frictional pressure loss in turbulent flow for drilling fluids containing high concentrations of long-chain polymer viscosifiers. This is due to the tendency of viscoelastic polymers to act as drag reducers in turbulent flow, a phenomenon for which no universally accepted modeling technique exists in the drilling industry (API, 2010).

In laminar flow, however, the equations utilized showed acceptable accuracy regardless of polymer concentration. This observation was expected, as the modeling methods for both the laminar and turbulent flow regimes are based on rheological parameters measured in laminar flow.

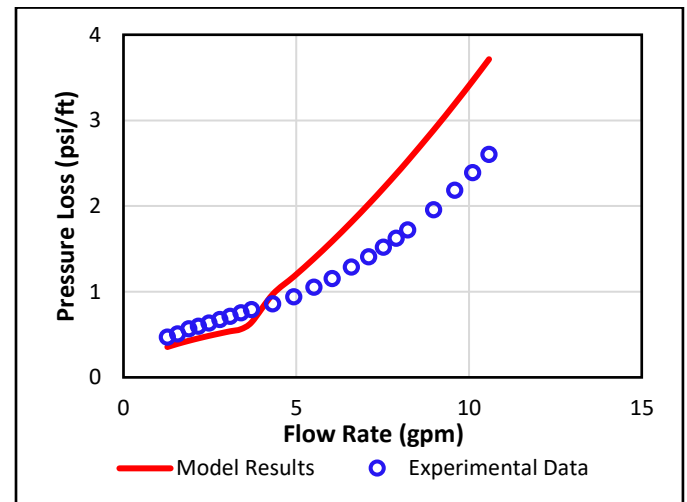


Figure 12: Comparison between experimental data and model for cesium formate brine containing 2.0 lb/bbl xanthan at 150°F.

Effect of Temperature on Frictional Pressure Loss

Data from fluids with identical polymer concentrations tested at differing temperatures were compared to gain insight into the effect of temperature on frictional pressure loss. As expected, experimental results showed a decrease in pressure losses with increasing temperatures in the laminar, transitional and turbulent flow regimes. However, the effect of temperature was observed to diminish beyond 150°F during experimentation with different polymer concentrations. Figure 13 shows pressure loss vs flow rate data collected from the ½" OD test section at three different temperatures (100°F, 150°F and 230°F) in cesium formate brine with a polymer concentration of 2.0 lb/bbl.

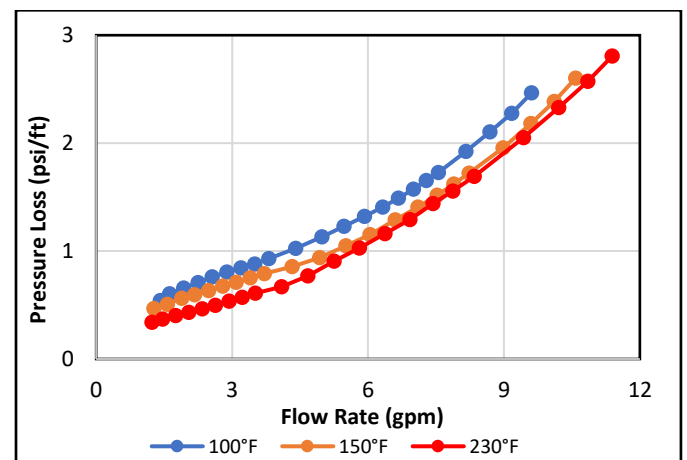


Figure 13: Frictional pressure loss in cesium formate brine containing 2.0 lb/bbl of xanthan gum at 100°F, 150°F and 230°F for the ½" OD test pipe

Common industry practice for drilling mud rheology measurement involves testing at only one temperature, complicating any attempt to accurately model the complex behavior demonstrated here. These observations support the importance of real-time friction factor monitoring for more effective ECD management.

Effect of Shear Degradation on Frictional Pressure Loss

Experimental results thus far have proven that fluid composition and temperature have significant effects on frictional pressure loss and the accuracy of drilling hydraulics calculations. These are two of many factors that must be considered when performing high-fidelity hydraulic calculations. Variation of fluid characteristics over time is another important factor in this process.

To evaluate how the previously described polymer behavior is affected by time, frictional pressure loss was measured before and after fluids of identical polymer concentration experienced several hours of shearing within the experimental setup. **Figure 14** shows pressure loss vs. flow rate data collected before and after a fluid containing 1.25 lb/bbl xanthan was sheared for approximately 10 hours. Reynolds numbers during these tests ranged from 220 to 8320 for the un-sheared fluid and from 620 to 10,530 for the sheared fluid. In laminar flow the un-sheared fluid showed higher frictional pressure losses compared to the sheared fluid. In turbulent flow, however, the un-sheared fluid displayed decreased frictional pressure losses in comparison to the heavily sheared fluid.

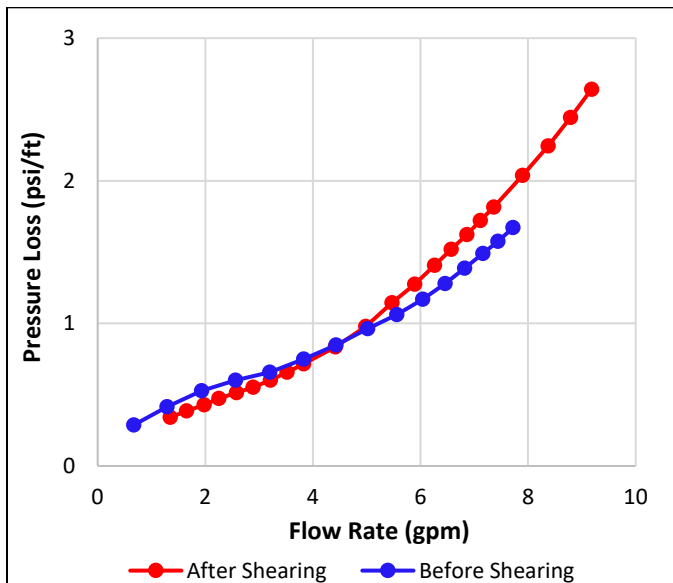


Figure 14: Frictional pressure loss in cesium formate brine containing 1.25 lb/bbl of xanthan gum at 100°F before and after shearing.

Interestingly enough, these two lines intersect and cross near the transition to turbulence the same way that data series from different polymer concentrations do in **Figures 5 and 7**. The relationship between the two curves therefore resembles

the trend between two fluids with slightly different polymer concentrations.

The tendency of long-chain polymer fluids to degrade at high shear rates has been extensively documented in literature (Fisher and Rodriguez, 1971; Tsau et al., 1992; Karami et al., 2018). Polymer degradation due to shear degrades the polymer's effectiveness at reducing frictional pressure losses, complicating drilling hydraulics modeling. These complications are likely to produce erroneous prediction of frictional pressure drop and ECD accordingly, highlighting the importance of real-time automated measurements of friction factor for hydraulic planning and ECD management.

Demonstration of Data-Driven Prediction

As the data from this study demonstrate, existing methods for predicting frictional pressure losses are inadequate for modeling polymer drilling fluids in turbulent flow. The next step in this investigation is to introduce a method to predict frictional pressure loss based on data collected in turbulent flow.

To accomplish this, data from a single test was filtered to include only turbulent data points and used to generate a graph of friction factor vs. Reynolds number, shown in **Figure 15**. A power law equation was then fitted to the data series. This equation was used to predict pressure readings for the same turbulent data points, allowing the accuracy of this prediction method to be evaluated. An R^2 value of 0.9896 was obtained for the curve fit, and a visual inspection of the trend line when compared to the experimental data shows that the fit correlates very well with the data series.

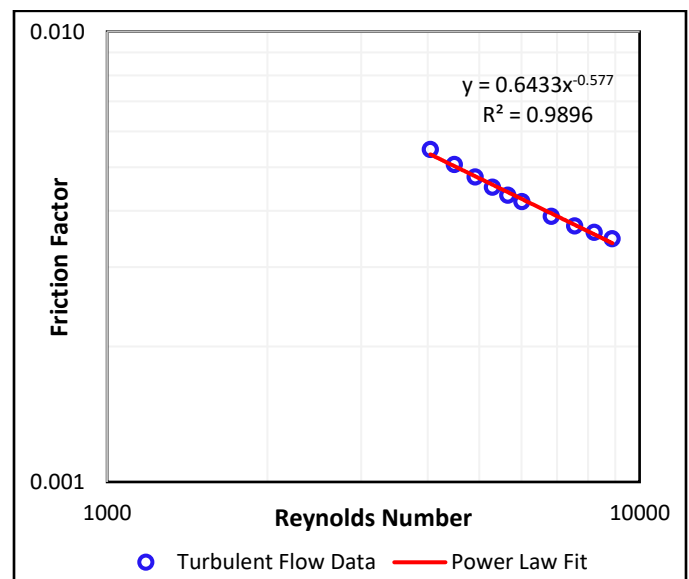


Figure 15: Friction factor vs. Reynolds number data for cesium formate brine containing 2.5 lb/bbl of xanthan gum tested at 100°F.

After the equation from this curve fit was used to “predict” the pressure readings for the entire test, experimental values were compared to the pressure readings simulated using this method. **Figure 16** shows the results of this pressure prediction, with the previously evaluated model included for comparison.

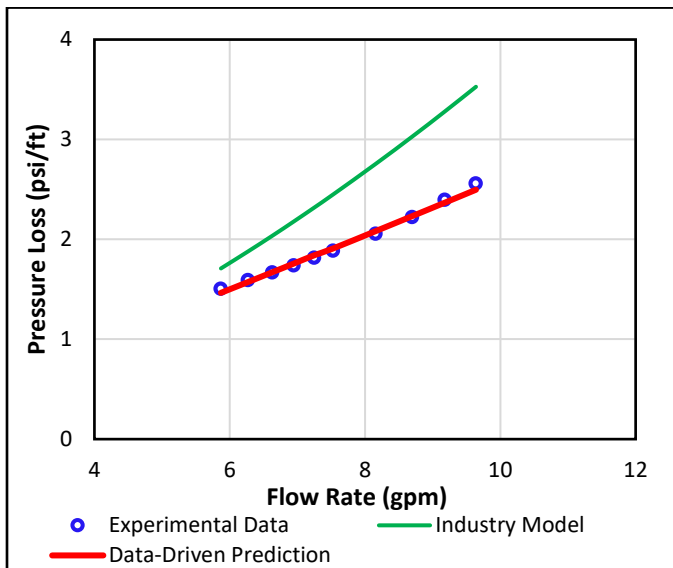


Figure 16: Results of real-time friction factor determination for a fluid containing 2.5 lb/bbl of xanthan at 100°F, compared to the previously evaluated industry standard method.

The real-time measurement method generated a maximum error of 2.0% for a single data point, compared to an error of 38.0% for the industry model. Average error values across the entire data series were 1.3% and 19.9% for the curve fit and industry prediction methods, respectively. Clearly, the real-time determination method provides substantially more accurate results than the established industry method.

Conclusions

- In this study, we investigated the frictional pressure loss behavior of several non-Newtonian long chain polymer-based fluids at concentrations up to 2.5 lb/bbl. Tests were conducted using a fully automated high temperature pipe viscometer at temperatures ranging from 100-230°F. Data was gathered in laminar, transitional and turbulent flow and results were compared to commonly used industry models.
- Significant discrepancy was observed between theoretical predictions and experimental results. The theoretical model evaluated underestimated the pressure losses of long-chain based polymer fluids in laminar flow while overestimating them in the turbulent flow regimes. This discrepancy is due to the models not properly accounting for the unique behavior of long-chain polymers in different flow regimes, with the polymers acting as viscosifiers in the laminar range but as drag reducers in the transitional and turbulent ranges. Considering the extensive use of long-chain polymer additives in well construction operations, relying on theoretical models for laminar, transitional or turbulent flow regimes is not advisable.
- An increase in polymer concentration is observed to delay the transition from laminar to turbulent flow. Furthermore, a more sophisticated model is required for correctly estimating the friction factor of long-chain polymer fluids.

- The friction factor was studied as a function of Reynolds for various polymer concentrations at different temperatures (100°F, 150°F and 230°F). The data can be used as a basis for friction factor estimation in the field.
- An increase in temperature decreases the pressure losses in long-chain polymer fluids in the laminar, transitional and turbulent flow regimes. However, the effect of increasing temperature grows less significant beyond 150°F.
- Degradation of long chain polymer fluids has been observed as expected, clearly indicating the need for real-time automated measurement of friction factor for hydraulic planning and ECD management. When polymer degradation occurs over time, a decrease of the pressure loss in the laminar range is observed, while an increase in the pressure loss in the turbulent range is seen.
- With the growing use of new materials in drilling, cementing and completion fluids, the behavior of fluids in different flow regimes is becoming more challenging to predict for effective hydraulic modeling and ECD management. This is of particular importance in special operations involving DGD and MPD technology applications on challenging wells such as (ultra-)deepwater, ERD and slim-hole. Applying real-time automated fluid characterization techniques as discussed in this paper provides vital insight in fluid management for these operations.

Nomenclature

A	= area, m ²
D	= diameter, m
f	= friction factor
K	= consistency index, Pa.s ^{m}
m	= fluid behavior index
N	= generalized flow behavior index
l	= length, m
p	= pressure, Pa
Q	= flow rate, m ³ /s
r	= radius, m
Re	= Reynolds number
V	= velocity, m/s
ρ	= density, kg/m ³
τ	= shear stress, Pa
τ_w	= shear stress at the wall, Pa
τ_y	= yield stress, Pa
$\dot{\gamma}_w$	= shear rate at the wall, 1/s

Glossary

<i>ECD</i>	= Equivalent circulating density
<i>ERD</i>	= Extended reach drilling
<i>DGD</i>	= Dual gradient drilling
<i>MPD</i>	= Managed pressure drilling
<i>YPL</i>	= Yield power law
<i>PL</i>	= Power law
<i>SBM</i>	= Synthetic-based mud
<i>WBM</i>	= Water-based mud

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