AADE
AMERICAN ASSOCIATION
of DRILLING ENGINEERS

AADE-17-NTCE-017

Application of Vane Viscometers to Estimate Drilling Fluids Rheology

Sandeep D. Kulkarni, Jessica Paola Ramirez-Angulo, Dale Jamison, and Lalit Mahajan, Halliburton

This paper was prepared for presentation at the 2017 AADE National Technical Conference and Exhibition held at the Hilton Houston North Hotel, Houston, Texas, April 11-12, 2017. This conference is 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

Viscometers with vane geometry are used as a standard rheometry technique. Within the oilfield industry, vane viscometers are used to measure the yield stress of drilling, completion, and cementing fluids, in particular. As the fluid structure is not disturbed before measurement and wall slip effects are minimized, vane geometry is useful for characterizing the rheological properties of a gel. This paper provides methods to extend the application of vane geometry to predict the viscosity of wellbore fluids at a range of shear rates, thus providing an alternative to using conventional viscometers.

Fluid behavior in vane shear flow was investigated for several fluids, including Newtonian liquids as well as drilling fluids that demonstrate shear thinning and yield stress behavior. Unlike conventional bob-sleeve couette viscometers, vane viscometers are less sensitive to eccentricity between the vane and sleeve. Another advantage of vane viscometers is their ability to handle fluids containing larger particles, especially those greater than 500 µm. However, flow in vane geometry generates vortices at high shear rates. This challenge was overcome by extrapolating the behavior at low and moderate shear rates with reasonable accuracy.

The eccentricity tolerance of the measuring geometry and the ability to handle fluids containing lost circulation materials (LCM) and cuttings contamination make vane viscometers practical for various laboratory and field environments. The derived rheology information can be used for wellbore pressure management.

Introduction

Vane viscometers have been used to evaluate the gel structure of various products, such as dessert, yogurt, and sauces. Shear-sensitive samples can be tested with vane spindles without changing their structural integrity. The three-dimensional (3D) structure of the fluid might be destroyed when a standard measuring system bob is immersed; hence, for such samples, vane geometry is preferred. It has been shown to be ideal for measuring the yield stress of concentrated suspensions[1]. In the oilfield, vane geometry has been used to determine the yield stress of bentonite suspensions[2] and invert emulsion fluids[3]. Additionally, vane geometry measurements can be performed in-situ in containers or cans because the viscometers are less sensitive to the eccentricity between the vane and container[4].

The bob-sleeve geometry of conventional oilfield viscometers provides rheological characterization at a broad range of shear rates from 5 to 1020 s^{-1} for drilling fluids, but given the geometry constraint, conventional viscometers can only be used as long as the fluids contain smaller particulates ($d_{50} < 500$ µm)[5]. If vane viscometers could provide rheological characterization at a reasonable range of shear rates, they would be useful for determining the rheological behavior of fluids containing large LCMs. Large-size particulates are often used for LCM applications in highly depleted formations[6]. The effect of LCM addition on the rheology of drilling fluids and, correspondingly, on the equivalent circulating density (ECD), has been shown to be an important criteria for LCM selection[7]. Some studies use a wider gap between the bob and rotor in the coquette geometry to perform rheological measurements of fluids containing particles up to 2 mm in size[8]. However, the literature lacks comprehensive methods to predict and manage the rheology of fluids that contain large-sized LCMs. This challenge is addressed by providing methods for determining the rheology of the drilling fluids using vane viscometers that can potentially handle a broader range of particle sizes.

Experiments: Viscometers

Conventional Viscometer

API-recommended viscometers have a specific bob and rotor geometry, as shown in **Fig. 1**. The bob is attached to a torque measurement device. The torsion spring resists rotational torque of the sheared sample disposed in the annulus between the rotor and the bob. As the rotor spins, torque is applied to the bob, which results in deflection of the bob. The deflection is measured by a dial (or a position encoder). The degree of rotation is proportional to the shear stress. The conventional rotor bob combination, R1/B1, has a gap of approximately 1.0 mm.

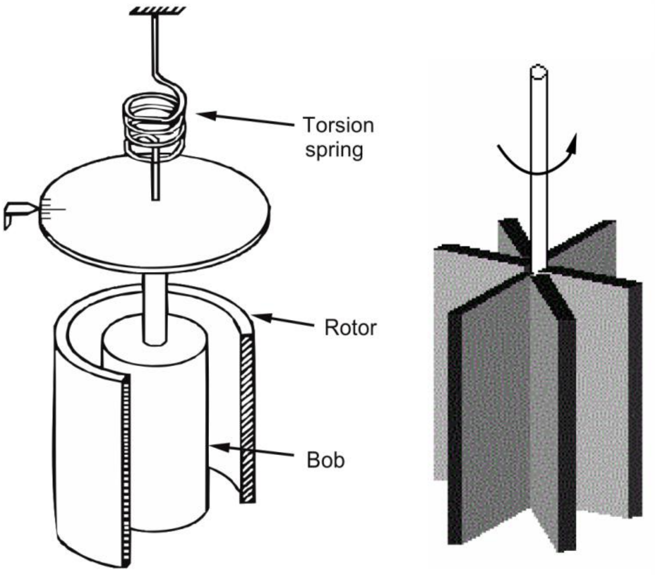

Fig. 1—Schematic of (i) a rotor and bob combination of a conventional API viscometer; (ii) six-blade vane geometry of an advanced viscometer.

Vane Viscometer

A six-blade vane viscometer was used for the measurements. The height of each vane blade is 17 mm, the diameter of the geometry is 22 mm, and the diameter of the cylindrical container in which the fluid is placed is 27 mm. The vane geometry is attached to a torque measurement device. For the fluid rotational test, the rotational speed (min^{-1}) vs. torque [mNm] data are recorded.

As the shear rate across the vane and cylinder gap is not uniform, the measured values are generally approximate. A geometry-based conversion factor, established based on the calibration of known fluids, is used to transform the torque vs. speed data into shear stress vs. shear rate.

Experiments: Drilling Fluid Formulations

As shown in **Table 1**, a clay-free, water-based drilling fluid was formulated with a mud weight of 12 lbm/gal. A Hamilton Beach mixer was used to mix the fluid. Each fluid component was added on-the-fly while mixing, as described below. The mixing time of each component addition was kept consistent as several samples of the fluid were formulated.

After mixing, the fluid samples were transferred to 1000-mL glass jars and then placed in a roller oven for hot-rolling at 150°F for 16 hours.

Table 1—Clay-free, Water-based Drilling Fluid Formulation.

Component	Amount	Mixing Time (min)
Water (lbm/bbl)	As required	—
NaCl (lbm/bbl)	As required (200,000-ppm brine)	5
Viscosifier (lbm/bbl)	1.5	10
Shale Stabilizer I (lbm/bbl)	7.25	5
Shale Stabilizer II (lbm/bbl)	1.25	5
Shale Stabilizer III (lbm/bbl)	6.4	5
Barite (lbm/bbl)	As required	15
Mud weight: 12 lbm/gal		

The same mixing and hot-rolling process was used to formulate a clay-based, water-based drilling fluid with a mud weight of 8.5 lbm/gal, as shown in **Table 2**.

Table 2—Clay-based, Water-based Drilling Fluid Formulation.

Component	Amount	Mixing Time (min)
Water (lbm/bbl)	As required	—
Bentonite (lbm/bbl)	14.7	30
Filtration control agent (lbm/bbl)	0.42	5
Shale stabilizer (lbm/bbl)	0.42	15
Mud weight: 8.5 lbm/gal		

Experiments: Methodology

Test Matrix for Statistical Analysis

Three samples were prepared for each fluid to study the part-to-part variation. Each sample was tested on two differently calibrated viscometers of each type (conventional and vane) to investigate the reproducibility of the data. On each calibrated viscometer, two measurements were obtained to confirm the repeatability of the data. Overall, 12 data sets (**Fig. 2**) were obtained for each fluid-viscometer combination for statistical analysis of the data and model development.

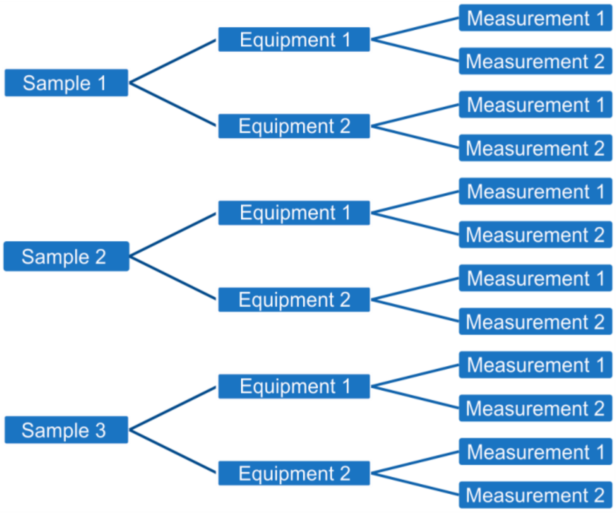

Fig. 2—Test matrix for statistical analysis of each fluid.

Conventional Viscometer Rheology

The rheology of the hot-rolled drilling fluid samples was measured at 120°F using a conventional API viscometer with a rotor-bob combination (gap approximately 1 mm). The conventional viscometer operates at six speeds, ranging from 3 to 600 RPM. The fluid was heated to 120°F using the viscometer heater assembly, and then test data were obtained.

Vane Viscometer Rheology

This test was conducted on an advanced rheometer assembly. Approximately 40 mL of drilling fluid was added to a cylindrical container. The cylinder was tapped for 2 minutes to remove any possible bubbles in the sample. The cylindrical container was then placed in the Peltier assembly. The fluid temperature was maintained at 120°F using the Peltier temperature control system. The six-blade vane geometry, which was attached to the instrument measuring system, was lowered into the fluid sample to the "zero" position. The vane was then rotated at various shear rates, and shear stress vs. shear rate data were recorded.

Results and Analysis

Fig. 3 shows variation analysis of the 12 data sets obtained using the conventional viscometer for the clay-free, water-based drilling fluids. The measurement error increases with increasing speed from 3 to 600 RPM, as shown in **Fig. 3a**. For instance, the mean dial reading (unit: lbf/100 ft^2) at 6 RPM is 11.1 with a standard deviation of 0.4, while the mean dial reading at 300 RPM is 40.7 with a standard deviation of 1.1. **Fig. 3b** shows further statistical analysis of the standard deviation: the error from repeatability and reproducibility (Gage R & R) of the data is dominant compared to that from the part-to-part sample variation of the fluid.

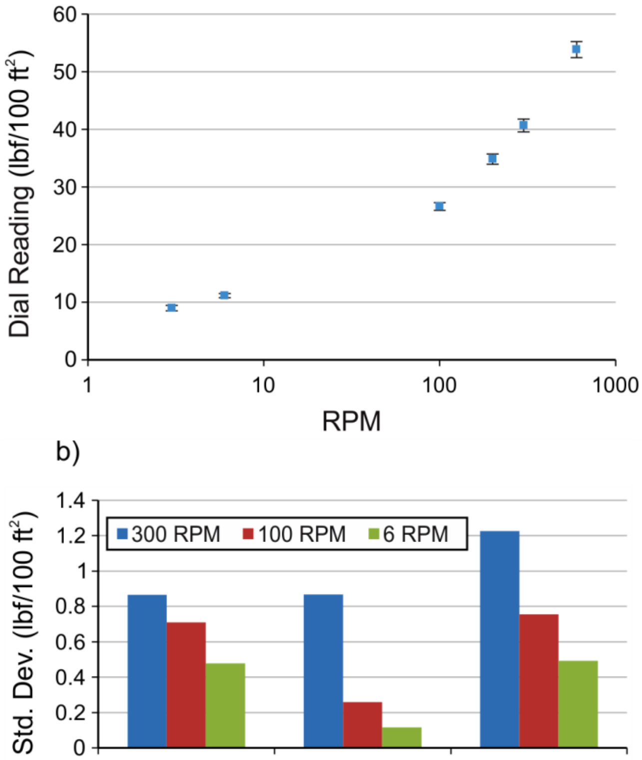

Fig. 3—Variation analysis of conventional viscometer data on clay-free, water-based drilling fluid (12 data sets): (a) mean and standard deviation at each RPM and (b) statistical analysis of 300, 100, and 6 RPM data.

Fig. 4 shows variation analysis of the 12 data sets obtained using the conventional viscometer for the clay-based, water-based drilling fluids. Similar to the clay-free system, the measurement error increased with increasing speed, from 3 to 600 RPM. A maximum standard deviation dial reading of 1.2 was observed for the 600-RPM dial reading data.

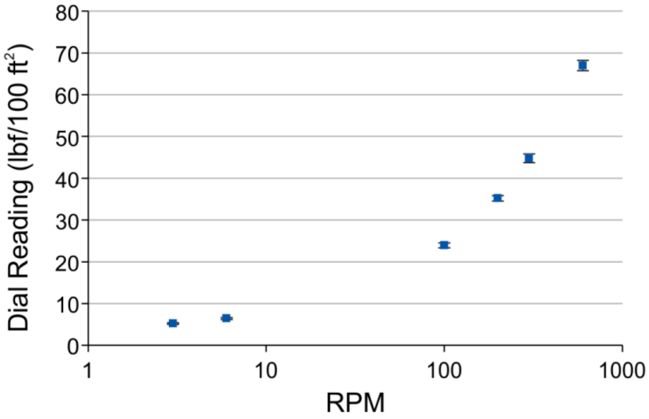

Fig. 4—Variation analysis of conventional viscometer data on clay-based, water-based drilling fluid (12 data sets): mean and standard deviation at each RPM.

Appendix I shows the representative data set obtained using the vane geometry on an advanced rheometer setup for clay-free and clay-based, water-based fluids. Overall, the 12 data sets obtained on the vane for each fluid showed excellent consistency, with a standard deviation of ± 1 Pa. The data obtained from the vane beyond a shear rate of 170 s^{-1} (100 RPM FANN®-35 viscometer equivalent) appeared to be strongly affected by vortices, and the effect needs to be accounted for when transforming the vane data in shear-stress vs. shear rate form. An analytical model was developed to transform the vane data into shear-stress vs. shear-rate form.

Fig. 5 compares the vane-based model prediction with that of a conventional viscometer for the clay-free fluid. The representative case in **Fig. 5a** shows that the model prediction curve begins similarly to the conventional viscometer data. At 300 RPM, statistical analysis (**Fig. 5b**) shows that the mean difference between the vane-based model prediction and conventional viscometer data was a dial reading of 2.4 (lbf/100 ft^2) with a 95% confidence interval of [1.2, 3.5]. At 100 RPM, statistical analysis (**Fig. 5c**) shows that the mean difference between the vane-based model prediction and conventional viscometer data was a dial reading of 0.5 (lbf/100 ft^2), with a 95% confidence interval of [0.1, 1]. At 6 RPM, statistical analysis (**Fig. 5d**) shows that the mean difference between the vane-based model prediction and conventional viscometer data was a dial reading of 2.9 (lbf/100 ft^2), with a 95% confidence interval of [2.7, 3.3].

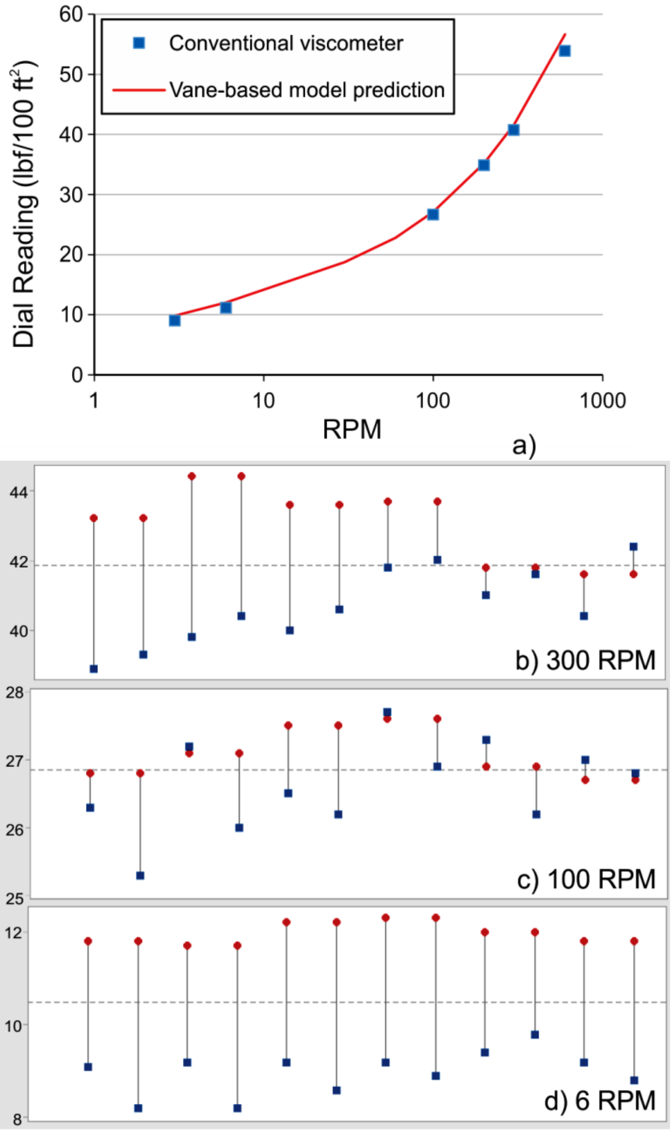

Fig. 5–Comparison of vane-based model prediction (red line and red circles) with conventional viscometer data (blue squares) for clay-free, water-based muds for (a) a representative sample set range from 600 to 3 RPM; (b) 300 RPM data for 12 sample sets; (c) 100 RPM data for 12 sample sets; and (d) 6 RPM data for 12 sample sets.

Fig. 6 compares the vane-based model prediction with the conventional viscometer for the clay-based, water-based fluid. The representative case in **Fig. 6a** shows that the model prediction curve begins similarly to the conventional viscometer data. At 300 RPM, statistical analysis (**Fig. 6b**) shows that the mean difference between the vane-based model prediction and conventional viscometer data was a dial reading of -3.1 (lbf/100 ft^2), with a 95% confidence interval of [-3.9, -2.4]. At 100 RPM, statistical analysis (**Fig. 6c**) shows that the mean difference between the vane-based model prediction and conventional viscometer data was a dial reading of -0.7 (lbf/100 ft^2), with a 95% confidence interval of

[-1, -0.3]. At 6 RPM, statistical analysis (**Fig. 6d**) shows that the mean difference between the vane-based model prediction and conventional viscometer data was a dial reading of 2.5 (lbf/100 ft^2), with a 95% confidence interval of [2.2, 2.8]. A further investigation to reduce the statistical error, especially at the low RPMs, is warranted.

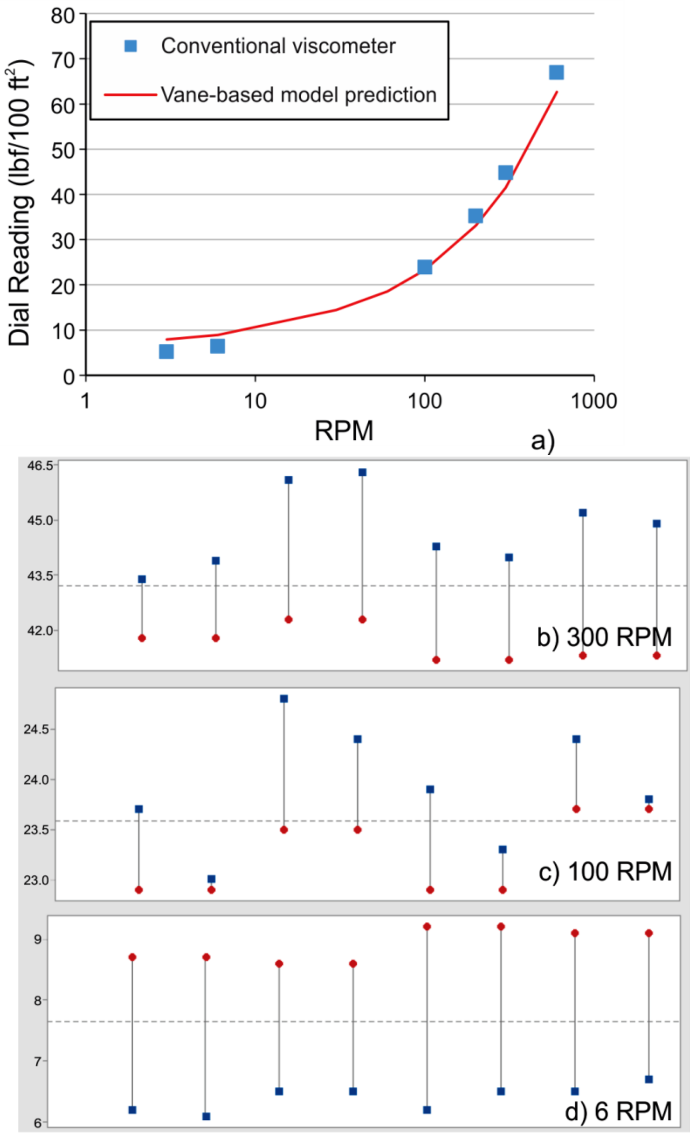

Fig. 6—Comparison of vane-based model prediction (red line and red circles) with conventional viscometer data (blue squares) for clay-based, water-based muds for (a) a representative sample set range from 600 to 3 RPM; (b) 300 RPM data for 12 sample sets; (c) 100 RPM data for 12 sample sets; and (d) 6 RPM data for 12 sample sets.

Conclusions

The following conclusions are a result of this study.

- The vane-based model predictions reasonably agree with conventional viscometer measurements, particularly at low and moderate shear rates.
- The vane geometry and model can be used for hydraulics calculations and measuring the viscosity of water-based fluid systems containing a broad range of particle sizes.

Acknowledgments

The authors thank Halliburton management for permission to present this work.

FANN® is a registered trademark of Fann Instrument Company, Houston, Texas.

Nomenclature

ECD = *equivalent circulating density*
gpm = *gallons per minute*
lbm/gal = *pounds per gallon*
lbm/bbl = *pounds per barrel*
LCM = *lost circulation materials*
ppm = *parts per million*
RPM = *revolutions per minute*

References

1. Dzuy, N.Q. and Boger, D.V.: “Yield Stress Measurements for Concentrated Suspensions.” Journal of Rheology, Vol. 27, Issue 4 (1983).
2. Alderman, N.J., Meeten, G.H., and Sherwood, J.D.: “Vane Rheometry of Bentonite Gels.” Journal of Non-Newtonian Fluid Mechanics, Vol. 39, Issue 3 (1991) 291–310.
3. Zanten, R.V., Miller, J.J., and Baker, C.: “Improved Stability of Invert Emulsion Fluids.” Paper IADC/SPE 151404 presented at the 2012 IADC/SPE Drilling Conference and Exhibition, San Diego, California, USA, 6–8 March 2012.
4. Parker, A. and Vigouroux, F.: “Texture profiling with the vane for characterizing the rheology of shear-sensitive soft foods.” International Symposium of Food Rheology and Structure (2003).
5. Misra, G., Jamison, D.E., and Whitfill, D.: “Effect of Drill Solids on the Prediction Accuracy of a Viscosity Model.” Paper SPE 142299 presented at the SPE Middle East Oil and Gas Show and Conference, Manama, Bahrain, 25–28 September 2011.
6. Whitfill, D., Jamison, D., Wang, H., and Thaemlitz, C.: “New Design Models and Materials Provide Engineered Solutions to Lost Circulation.” Paper SPE 101693 presented at the Russian Oil and Gas Technical Conference and Exhibition, Moscow, Russia, 3–6 October 2006.
7. Majidi, R., Edwards, S., Zhang, J., Randall, S., and Nigel, L.: “Drilling Depleted Sands: Geomechanics, Challenges and Mitigations.” Paper SPE 174741 presented at the SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, 28–30 September 2015.
8. Kulkarni, S.D., Savari, S., and Fowler, D.: “Predicting Rheology of Drilling Fluids Containing Large Sized LCMs.” Paper AADE-16-FTCE-67 presented at the AADE Fluids Technical Conference and Exhibition, Houston, Texas, USA, 12–13 April 2016.

Appendix I

Table 3—Representative Data-sets for Clay-free, Water-based Drilling Fluid Viscosity Using the Vane Geometry on an Advanced Viscometer.

Parameter	**Equipment 1**	
	Measurement 1	**Measurement 2**
Test temperature (°F)	120	120
Advanced Viscometer Readings (Pa)		
510 s^{-1}	87.9	89.1
340 s^{-1}	45.6	46.3
170 s^{-1}	27.2	27.5
102 s^{-1}	22.8	22.8
52 s^{-1}	18.8	18.6
10.2 s^{-1}	12	11.9
5.1 s^{-1}	9.9	9.7
10-Second gel	10.9	10.5
10-Minute gel	13.6	13.4

Table 4—Representative Data-sets for Clay-based, Water-based Drilling Fluid Viscosity Using the Vane Geometry on an Advanced Viscometer.

Parameter	**Equipment 1**	
	Measurement 1	**Measurement 2**
Test temperature (°F)	120	120
Advanced Viscometer Readings (Pa)		
510 s^{-1}	64.7	65.8
340 s^{-1}	37.2	38.2
170 s^{-1}	23.2	23.8
102 s^{-1}	18.4	18.8
52 s^{-1}	14.3	14.4
10.2 s^{-1}	8.8	8.7
5.1 s^{-1}	7.8	7.6
10-Second gel	7	7
10-Minute gel	13.3	12.2