Proceedings Australian Geothermal Energy Conferences 2013
Brisbane, Australia, 14-15 November 2013

Techniques for Accurate Characterisation of Aqueous High Temperature Drilling Fluids with Slip

Aleks D. Atrens*, Jason R. Stokes

*Queensland Geothermal Energy Centre of Excellence, School of Mechanical & Mining Engineering,

The University of Queensland, Brisbane, Australia

aleks.atrens@uq.edu.au

Keywords: Geothermal; High Temperature; HPHT; Drilling Fluids; Rheology; Slip.

ABSTRACT

Drilling fluids are an important component of cost-efficient drilling of geothermal wells. Drilling fluids typically have a composition to position them on the boundary between solid-like and liquid-like behaviour. Operating at this boundary makes their behaviour sensitive to changes in fluid ionic strength, pH, solids content, and most importantly for geothermal drilling operations, temperature. Changes in these conditions can alter their yield stress and high-shear viscosity. Measurement techniques to accurately characterise their yield stress behaviour and high-shear viscosity are vital. Here we show that rheological characterisation is critically dependent on geometry selection. Measurements of an aqueous Hausmannite suspension showed evidence of slip when using a concentric cylinder geometry, and evidence of secondary flow when using a vane geometry. The concentric cylinder geometry – the most common in industrial use – can provide misleading yield stress or gel strength results due to slip at the smooth surfaces. Prediction of drilling fluids behaviour at *in situ* conditions requires considered use of multiple geometries to ensure that rheological characterisation is robust and not subject to confounding measurement errors. This work provides a foundation for accurate drilling fluids characterisation at elevated temperatures.

1. INTRODUCTION

Drilling fluids fulfil a number of different requirements during drilling operations, most notably:

- Cleaning the well by lifting, suspending, and removing cuttings;
- Providing additional density to maintain well control;
- Minimising pumping requirements;
- Cool the bit and bottom-hole apparatus;
- Lubricate the drill string, minimising wear;
- Transfer power to down-hole motors if present in the bottom-hole apparatus;
- Stabilise mineral formations that may otherwise slough into the well; and
- Prevent loss of drilling fluid from the well into the drilled formations.

Of these, the most important rheological goals are effective well cleaning – removal of drilling cuttings from the well– and low resistance to flow – to minimise pumping power requirements and reduce dynamic pressure changes. These characteristic rheological needs are met by a combination of a non-zero but small "yield stress" – industrially known as "gel strength" – with a low viscosity at high shear rates. The yield stress maintains suspension of cuttings in the drilling fluid, and assists in maintaining stable suspension of solid drilling fluid components. The low viscosity at high-shear rates ensures that pressure drop over the length of the drill string is small. An example of both 'typical' drilling fluid behaviour, and 'ideal' behaviour calculated from hydraulic modelling of drilling operation is shown in Figure 1.

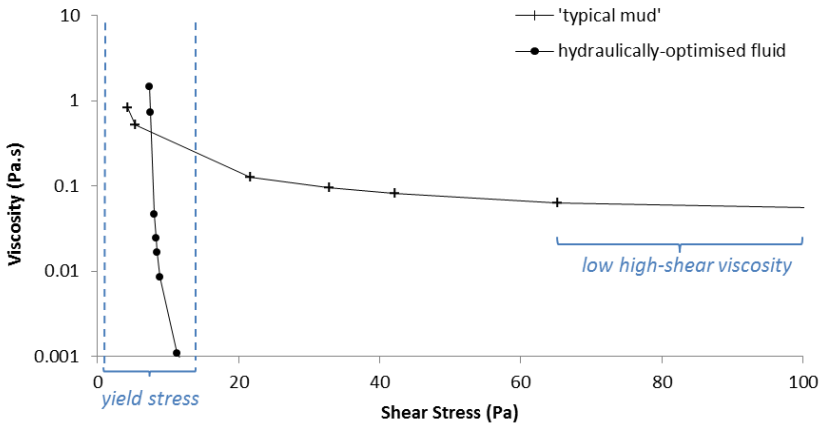


Figure 1: Viscosity versus shear stress for a 'typical' drilling fluid, and for fluid properties computed to provide optimum hydraulic and well-cleaning behaviours; adapted from Zamora and Grocock (2010).

Typically, this combination of different rheological behaviours is achieved by designing a fluid that exists at the boundary between solid-like and liquid-like rheology. This is typically achieved by formulating a drilling fluid mixture that can form network structures. This can be achieved simply (although rarely in practice) through suspended solids at large effective volume fractions, where solid-like properties are derived from inter-particle collisions at concentrations approaching maximum packing behaviour. Network structures are also achievable through solids interacting to form distinct networks through flocculation. Bentonite, the most common clay added to drilling fluids can form 'house-of-cards' type flocculated networks, but also derives rheological behaviour from its structure of high aspect ratio platelets providing a large effective rheological volume in comparison to particle size (Luckham & Rossi, 1999). Finally, soluble polymers can also provide structural behaviour to drilling fluids, and are often provided by carbohydrate gums such as Xanthan or Guar. Network structures present in a drilling fluid can provide solid-like behaviour at moderate stresses while the fluid is only slightly sheared – such as when drilling fluid flow has ceased. The structures can reversibly break apart on exposure to high shear rates, thereby no longer significantly impeding flow (Pignon et al, 1998).

Because drilling fluids operate at the boundary of solid-like and liquid-like behavioural regimes, even small changes to their properties can substantially change behaviour. Small alterations of composition, pH, dissolved ions, or polymers can disproportionately alter the effective volume of solids or the flocculation behaviour, thereby having unexpected results. This sensitivity of drilling fluids presents a substantial challenge (Bland et al, 2006). Formulations mixed at the rig may not exactly match those prepared and tested in drilling fluid design laboratories. Ultra-fine particulates produced during drilling operations can be difficult to remove from the drilling fluid mixture, thereby providing an increase in total solids content, and different rheological behaviour of the suspended solids. Most importantly for geothermal operations, there is the challenge of high temperature altering behaviour.

2.1 High Temperature

Drilling fluids used to access high temperature resources will be exposed to high temperatures. During circulation, the operating temperatures are not as high as the reservoir temperature itself, due to counter-current heat exchange between the drill string the annulus of the well, and the use of mud chillers on the drill rig at the surface. However, for similar temperature reservoirs, the deeper the well, the higher the maximum circulating temperatures will be, due to heat exchange effects (Raymond, 1969). However as soon as circulation ceases, temperatures can increase quickly toward reservoir temperatures. In combination, these thermal effects mean that drilling fluids used in geothermal wells will be exposed in operation to a large range of temperatures under which they must be both stable and provide desirable rheological behaviour.

Exposure of drilling fluids to high temperatures can have a range of effects. Organic materials can thermally degrade, which becomes an increasingly challenging problem with higher temperatures due to reduction in range of stable options. Drilling fluid components may also become more likely to react with other fluid components, cuttings, or contaminants such as gases introduced from the drilled formations. Degradation or reaction can obviously substantially alter the rheological behaviour of a drilling fluid if critical components are lost or converted to rheologically-inert materials.

Additionally, the temperature itself can alter rheological behaviour of materials that are otherwise stable. It can change the interaction between suspended materials and the drilling fluid solvent, or the interaction between suspended particles. Most notably, this can alter flocculation behaviour. This can lead to unanticipated behaviour if fluids are not properly characterised at high temperature.

From this figure, it is obvious that non-linear changes can occur due to high temperatures. It is for this reason that the QGECE has a drilling fluid research program aimed to characterise the behaviour of key fluids at high temperature conditions, and evaluate the behaviour of potential new

2.1 Measurement Techniques

Rheological characterisation is performed using rheometers or viscometers, which use control over shear stress and shear strain rate of the fluid allow measurement of behaviour. The rheological can be characterised across a range of conditions comparable to the different flow regimes the drilling fluid may experience down-hole. Rheometer apparatus can typically be fitted with a number of different geometries, which allow for evaluation of different types of flow characteristics. In this work, both concentric cylinder and vane geometries were used. The concentric cylinder had a cylinder diameter of 14 mm a cup diameter of 15.02 mm, a height of 42.2 mm, and a gap during operation of 13 mm. The vane used had a diameter of 10.98 mm and a cup stator diameter of 21.7 mm.

Vane tools are typically used due to their acknowledged efficacy in laboratory rheology in effective characterisation of yield stress behaviour (Stokes & Telford, 2004). However, due to their large annular space, they are prone to secondary flow during shearing with low viscosity fluids. Concentric cylinders are designed to provide effective measurement of rheological behaviour over a wide range of shear rates. It is for this reason that they are widely used as the geometry of choice in oilfield viscometers and rheometers. However, due to the use of smooth metal surfaces, they are prone to surface effects. In particular, slip can occur, whereby due to a reduced concentration of suspended solids or dissolved material at the geometry surfaces, viscosity is locally reduced toward that of the bulk solvent. This results in an apparent ease of flow at a given stress larger than possible in the bulk fluid (Meeker et al, 2004). This can confound measurement of yield stress behaviour, providing a lower result than actually achievable in the fluid. Whether this occurs depends on the characteristics of the fluid.

Other common geometries are the cone-and-plate and parallel plate geometries. These can provide better variation in the size of the gap through which fluid flow occurs, allowing characterisation across a wider range of shear stresses and strains. However, they are also characteristically defined by a horizontal gap, which is prone to slip along the upper surface in suspensions which are unstable (which is the case for many drilling fluids).

2. CHARACTERISATION WITH DIFFERENT GEOMETRIES

An aqueous suspension of Hausmannite (Mn_3O_4) at 20% by volume was prepared by mixing of measured amounts of dry powder and distilled water in an electric mixer. Hausmannite, a material of high density (specific gravity of 4.7) is a potential weighting agent – used to increase the density of the drilling fluid – and also has characteristic rheological behaviour desirable in a drilling fluid of small yield stress and low flowing viscosity (Kar et al, 2011). It is used here as an example of the care that should be taken with rheological measurements.

The aqueous Hausmannite suspension was evaluated using concentric cylinder and vane geometries. This evaluation was conducted at ambient temperature and pressure to evaluate the measurement techniques that can be used to provide accurate results at the elevated *in situ* conditions. Both these geometries produced characteristically different results.

The rheological behaviour of the Hausmannite suspension as measured with the concentric cylinder geometry is shown in Figure 2. In Figure 2 is evident a constant high shear viscosity between 10 and 20 mPa.s, and ultimate yield stress behaviour between 1 and 2 Pa of shear stress. However, between these regions, there is an additional plateau of constant viscosity. This behaviour is typical of slip (Meeker et al, 2004). While this behaviour is apparent with this data set, a smaller range of measurements may not provide sufficient detail to notice this behaviour.

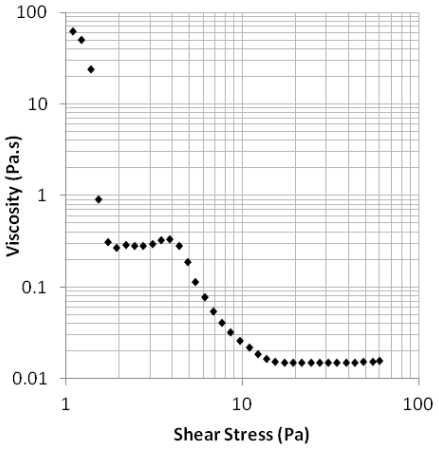


Figure 2: Viscosity versus shear stress for aqueous Hausmannite suspension measured using a concentric cylinder geometry; two constant viscosity plateaus are visible, with the one at a viscosity of 0.3 Pa.s being attributable to slip behaviour.

The rheological behaviour of the same suspension, as evaluated using the vane tool is shown in Figure 3. This figure demonstrates very clear yielding behaviour at a shear stress of approximately 3 Pa. However after yielding, no high-shear plateau is present, and the lowest viscosity measured is 0.2 Pa.s. Instead, a steady increase in viscosity with increasing stress is evident. While this type of behaviour can be evidence of secondary flow, it was evaluated further by a comparison with standards to confirm whether this was the case.

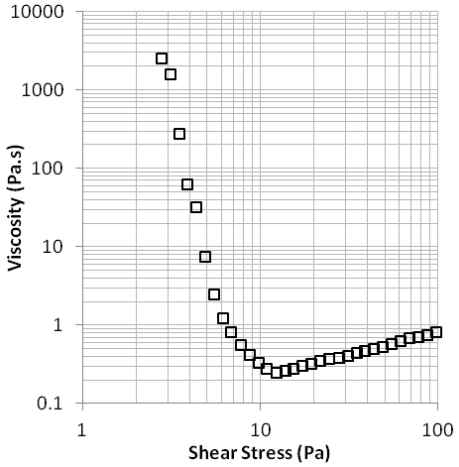


Figure 3: Viscosity versus shear stress for aqueous Hausmannite suspension measured using a vane tool; a linear increase in viscosity with shear stress at low stresses or rates is characteristic of secondary flow behaviour.

Silicon oil standards calibrated to provide a Newtonian viscosity of 100 CSt (0.1 Pa.s) were evaluated using both geometries. Their measured behaviour, as well as the data from Figure 3, is combined in Figure 4. Figure 4 Clearly demonstrates that both the vane geometry and the concentric cylinder geometry can accurately measure the Newtonian viscosity of the standards across a range of conditions. At very low stresses, both geometries become susceptible to errors in measurement caused by ambient noise, and measurements below a shear stress of 0.1 Pa are disregarded. When the silicon oil is measured at high shear stress (and thus shear

rate) with the vane tool, an increase in viscosity is measured. This must clearly be secondary flow behaviour. This coincides with the increasing viscosity evident in measurements of the Hausmannite suspension with the vane tool.

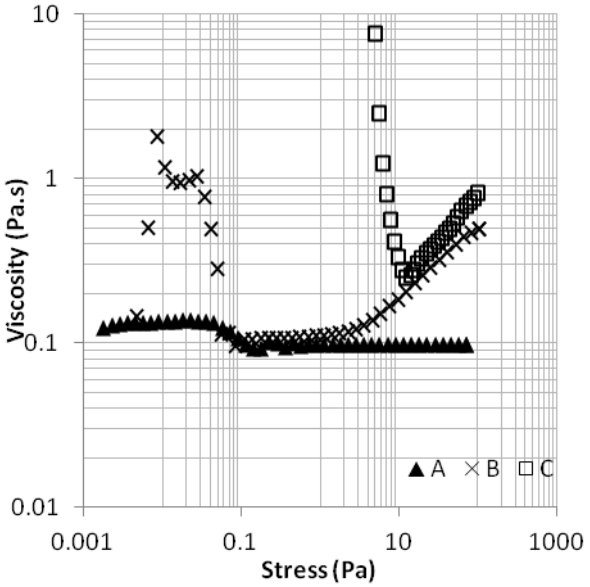


Figure 4: Viscosity versus Shear Stress for (A) 100 CSt Silicon Oil in concentric cylinder, (B) 100 CSt Silicon Oil in vane geometry, and (C) aqueous Hausmannite suspension in vane geometry; Below 0.1 pascals of shear stress, measurement noise becomes non-trival.

From this, it can be concluded that neither geometry individually provides accurate measurement of rheological behaviour. However, the accurate regions of both measurement techniques can be combined to provide a combined measurement encompassing overall rheological behaviour of the fluid. Figure 5 displays an interpreted rheological profile for the fluid as derived from the two measurement techniques. It is notable that the initial rise in viscosity evident with the concentric cylinder as stress is reduced aligns neatly with the lowest stress yielding behaviour measured with the vane tool; this alignment provides support for an integrated rheological profile.

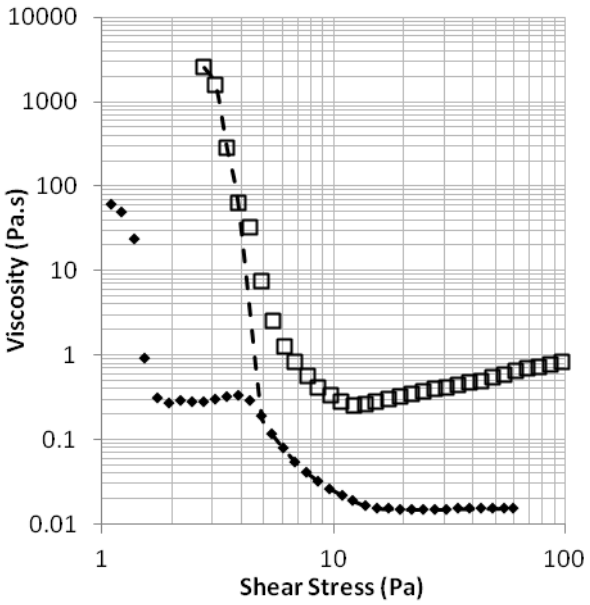


Figure 5: Viscosity versus shear stress for aqueous Hausmannite suspension measured using vane tool (squares) and concentric cylinder (diamonds); interpreted true behaviour is indicated with a dashed line which is fitted to exclude data where slip or secondary flow is present.

3. DISCUSSION

This analysis is aimed to provide a foundation for accurate characterisation of drilling fluids at the extreme conditions they will experience during geothermal drilling operations. It is evident that there are a number of important considerations to obtain a true understanding of actual fluid behaviour from rheological measurements:

- Individual geometries can be subject to confounding errors. In this instance, both geometries provide results that do not reflect the actual rheological behaviour of the fluid.
    - The use of a concentric cylinder system alone could lead to estimation of a much lower yield stress due to slip behaviour at the geometry surfaces. This is apparent only when compared to measurements with other geometries, or by a complete stress-rate curve with many measurement points. This slip behaviour would only be evident on polished surfaces with low roughness, and would not be encountered in drill pipe or rock surfaces down-hole.
    - The vane measurement geometry alone would lead to a substantial overestimation of high-shear viscosity. This behaviour is attributable to secondary flows present when the fluid is sheared at non-trivial rates. This is apparent from a comparison with measurements from rheological standard fluids, or by comparison with other geometries.
    - A combination of the results from both geometries is concluded to provide a prediction of actual flow behaviour of the bulk fluid under operating conditions (although at ambient temperature and pressure only).
- It is critical when interpreting rheological measurements to have an understanding of rheological behaviour. Proper assessment of the capabilities of rheological apparatus prior to evaluation of fluids of interest will ensure that shortcomings in the measurement approach are identified.
- Multiple geometries can be used as an approach to evaluate the robustness of the measurement approach. Using different approaches can provide a check as to the reliability of any individual approach. Where results diverge, it can provide a basis for determining which behaviours reflect actual behaviour down-hole.
- Hybrid geometries may also be suitable. If surface roughness is much larger than the characteristic size of suspended particles, surface effects are minimised and concentric cylinder geometries can be used without slip and with far less secondary flow behaviours than evident with the vane tool.
- The concern of obtaining an accurate rheological understanding of fluid behaviour is not purely academic. Misleading estimation of yield stress can lead to poor displacement of mud by space fluid prior to cementing and consequently incomplete cementing during completion. Differences from specification in any rheological property may lead to miscalculation of dynamic pressure changes during circulation or when running or pulling the drilling string. This can lead to well control issues or fluid loss into the reservoir with resulting formation damage.

The use of multiple geometries is proposed as a suitable method for evaluating the rheology of yield stress drilling fluids using a high temperature rheometer.

REFERENCES

Bland, R., Mullen, G., Gonzalez, Y., Harvey, F., Pless, M.: HP/HT Drilling Fluids Challenges. *IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition*, (2006), Bangkok, Thailand.

Kar, Y., Al Moajil, A.M., Nasr-El-Din, H.A., Al-Bagoury, M., Steel, C.D.: Environmentally Friendly Dispersants for HP/HT Aqueous Drilling Fluids Containing Mn_3O_4, Contaminated with Cement, Rock Salt, and Clay. *SPE Middle East Oil and Gas Show and Conference*, (2011), Manama, Bahrain.

Luckham, P.F., Rossi, S.: The colloidal and rheological properties of bentonite suspensions. *Advances in Colloid and Interface Science*, **82**, (1999), 43-92

Meeker, S.P., Bonnecaze, R.T., and Cloitre, M.: Slip and flow in pastes of soft particles: Direct observation and rheology. *Journal of Rheology*, **48**, (2004), 1295-1320.

Pignon, F. Magnin, A., Piau, J-M.: Thixotropic behaviour of clay dispersions: Combinations of scattering and rheometric techniques. *Journal of Rheology*, **42**, (1998), 1349-1373.

Raymond, L.R.: Temperature Distribution in a Circulating Drilling Fluid. *Journal of Petroleum Technology*, (1969), 333-341.

Stokes, J.R., and Telford, J.H.: Measuring the yield behaviour of structured fluids. *Journal of Non-Newtonian Fluid Mechanics*, **124**, (2004), 137-146.

Zamora, M. Grocock, F.: The Top 10 Myths, Misconceptions and Mysteries in Rheology and Hydraulics. *AADE Fluids Conference and Exhibition*, (2010), Houston, Texas.

.