Behaviour of Suspensions and Emulsion in Drilling Fluids

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Overview

• Introduction to drilling fluids
• Role of fluid rheology in the drilling operation
• Drilling fluid rheology; measurement & control
• Effect of rheology on hole cleaning
• Effect of rheology on barite sag
• Concluding remarks
Drilling Operation & Drilling Fluid

- A drilling fluid (mud) is a fluid containing one or more of the following, such that the objectives of the well or section to be drilled are achieved:
  - Aqueous phase (water, brine)
  - Non-aqueous phase (mineral oil, synthetic, diesel)
  - Solids (barite, clay, carbonate)
  - Gas (air, nitrogen)

![Diagram of drilling operation with mudcake and cuttings loss]

Functions of Drilling Fluids

Drilling fluids MUST be able to provide the following functions:

- Cooling & lubrication
- Cuttings suspension & removal (hole cleaning)
- Weight material (barite) suspension
- Balance formation pressure
- Maintain wellbore stability
- Minimise damage to formation
- Transmit hydraulic energy to tools & bit
- Control corrosion
- Allow formation evaluation
- Facilitate cementing & completion
- Minimise impact on environment

<table>
<thead>
<tr>
<th>Typical OBM Formulation</th>
<th>Kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base oil</td>
<td>478</td>
</tr>
<tr>
<td>Invert emulsifier</td>
<td>13</td>
</tr>
<tr>
<td>Wetting agent</td>
<td>13</td>
</tr>
<tr>
<td>Lime</td>
<td>22</td>
</tr>
<tr>
<td>Rheology additive</td>
<td>10 – 40</td>
</tr>
<tr>
<td>Fluid loss control additive</td>
<td>8.5</td>
</tr>
<tr>
<td>Brine</td>
<td>190</td>
</tr>
<tr>
<td>Barite</td>
<td>870</td>
</tr>
</tbody>
</table>
Drilling Mud Classification

Drilling fluids

- Oil-based fluids (mineral, synthetic, diesel)
  - All-oil fluids
  - Invert emulsions
- Water-based fluids
  - Polymer Fluids
  - Clay (gel) fluids
- Inhibitive
- Non-damaging

Some Measured Mud Properties

- Drilling fluids are complex multi-phase, multi-component systems whose properties undergo continuous change during the drilling operation.
- Change is caused by liquid lost to formation, addition of drill cuttings, chemical reactions, and temperature and pressure variations.
- To maintain their ability to perform, their properties must be monitored throughout the drilling operation so that corrective actions can be taken.
- The properties routinely measured are:
  - Rheology
  - Fluid loss
  - Oil/water ratio and emulsion stability for OBM
  - pH (WBM)
  - Density – lb/gal (ppg) or s.g.
  - High gravity & low gravity solids contents (HGS / LGS)
  - Salt content - usually as chlorides (WBM & OBM)
  - Inhibitor concentrations - K+, PHPA, glycol etc (WBM)
Rheology & Its Impact on Drilling Operation

- Pressure drop
- Hole cleaning (during flow)
- Cuttings suspension (during trips)
- Weight material suspension (barite sag)
- Hole stability
- Stuck pipe
- Swab & surge pressures
- Signal transmission (logging & measurement while drilling, well testing)
- Waste management

Rheology Additives for Drilling Fluids

- Clay-based WBM
  - Bentonite (platey)
  - MMO/MMH
  - Occasionally sepiolite or attapulgite (fibres)
- Polymer-based WBM
  - Xanthan gum
  - Celluloses
  - Occasionally guar gum, welan gum or polyacrylamide
- Invert emulsion fluids
  - Organophilic clay
  - Synthetic polymers
  - Aqueous emulsion
Clay-Viscosified Water-Based Fluids

- Bentonite clay: negative surface charge and positive edge charge of platelets produces highly shear-thinning house-of-cards structure.

- Mixed-metal oxide (MMO) has an electron-deficient lattice and, when added to water, the particles bond to the cation-exchange sites on bentonite, forming a strong complex, which in turn structures the fluid and provides gels and shear-thinning behaviour.

Polymer-Viscosified Water-Based Muds

- In conventional polymer muds, high MW polymers in aqueous solution generate rheology capable of suspending dispersed solids.

- In a novel high-temperature polymer mud, medium MW polymers adsorb on dispersed solids and interact with dissolved polymers to produce highly shear-thinning rheology.
Organoclay in Oil-Based Muds

- Organoclays are hydrophobically modified clays such as bentonite, hectorite, etc.

- In an invert emulsion fluid, hydrogen bonding between water molecules and OH⁻ groups of organoclay produces a weak network to enhance rheology in OBM.

Rheology Models Used for Drilling Fluids

- **Bingham**
  \[ \tau = YP + PV \dot{\gamma} \]

- **Power Law**
  \[ \tau = K\dot{\gamma}^n \]

- **Yield-Power Law**
  \[ \tau = \tau_y + k'\dot{\gamma}'' \quad \text{(Herschel-Bulkley)} \]
  \[ \tau^{1/2} = k_0 + k_1\dot{\gamma}^{1/2} \quad \text{(Casson)} \]
Rheology Measurement in Drilling Fluids

Rig-site measurements
- Marsh Funnel
  - Funnel viscosity (seconds/quart)
- Fann-type viscometer
  - Fixed rotational speeds
  - Shear rate range 5.11 – 1022 s⁻¹
  - Used to derive Bingham model parameters
    - Yield Point (YP)
    - High-shear-rate (HSR) viscosity, Plastic Viscosity (PV)
  - Some measure of thixotropy (10-sec & 10-min gel strength)
- Low-shear viscometer

Laboratory measurements
- Controlled rate and/or stress rheometers for in-depth study and characterisation of fluids

Rheology Measurement in Drilling Fluids: Fann-35 Viscometer

- Concentric cylinder (Couette)
- Outer cylinder rotates (rotor or sleeve)
- Inner cylinder measures torque (bob)

\[ R_1 = 1.8415 \text{ cm} \]
\[ B_1 = 1.7245 \text{ cm} \]
\[ L = 3.800 \text{ cm} \]
Measurement of Rheology: Fann 35

- For a curvilinear shear field, the shear rate at inner cylinder is given by:

\[ \dot{\gamma} = \frac{2R_1^2}{R_i^2 - B_i^2} \Omega \]

\[ \dot{\gamma} = 1.703 \, N \]

- Shear stress is given by the deflection (\( \theta \)) of the torsion spring which measures torque:

\[ \tau = 5.11 \, \theta \, \text{dyne/cm}^2 = 0.511 \, \theta \, \text{Pa} \]

\[ \tau = \theta \, \text{lb/in} / 100 \, \text{ft}^2 \]

Oilfield Definitions for Rheology: Fann 35

- For a Bingham fluid \( (\tau = YP + PV \cdot \dot{\gamma}) \)

\[ PV = \theta_{90} - \theta_{30} \, \text{cP} \]

\[ YP = 2 \theta_{300} - \theta_{600} = \theta_{300} - PV \, \text{lb/in} / 100 \, \text{ft}^2 \]

- LSR rheology is an important property of drilling fluids – it affects the solids bearing capacity of the fluids
- The Bingham model overestimates LSR rheology (in Fann-35 terms \( \leq 10 \, s^{-1} \))
- A more realistic \( YP \) can be defined by using the 6 & 3 rpm readings (the \( \text{LSYP} \)):

\[ \text{LSYP} = 2\theta_6 - \theta_3 \]
Comparison of Rheology Models

Deviation = Model - Measurement

Normalized Yield Points ($\tau_y / YP$)
(M. Zamora, et al., AAD-03-NTCE-35)

Based on > 11,000 oilfield mud samples
Fann-35 Measurements – Error Analysis

- Errors generally attributed to measurements of shear stress
- Relative error of measurements: \[
\frac{\Delta \tau}{\tau} = \pm \left[ 1.9 \times 10^{-7} + \frac{1}{4 \theta^2} \right]^{1/2}
\]

- A Fann reading of 5 may be in error by ±10%
  - A reading of 2 may be in error by ±25%
- Minimum error is ±0.5%

- Low readings and wall slip are major sources of error in Fann measurements

Wall Slip

- Fluid adjacent to a solid surface normally moves with velocity of that surface
- But, a velocity difference can occur through “wall slip”, caused by:
  - Depletion of solid particles in the layer near the wall (oil, water film), etc
  - Alignment of polymer molecules near the wall
- Slip gives erratic torque readings through stick-slip, and low stress
- Some drilling fluids are prone to wall slip during rheological measurements – e.g. bentonite muds, high viscosity pills, etc
- Where slip is present, measurements with different geometries will produce different flow curves
- To rectify:
  - Use roughened, grooved or cross-hatched metal surfaces
  - Alternatively, use the vane rheometer
Shear Rate

Drilling fluids experience a wide range of shear rates:

1. $O \times 10^3 \text{ s}^{-1}$ in drillpipe
   - Where low HSR viscosity is needed to reduce frictional pressure

2. $O \times 10^5 \text{ s}^{-1}$ through bit nozzles
   - Where high shear-thinning is needed to give high impact velocity

3. $O \times 10^2 \text{ s}^{-1}$ in annulus
   - High LSR viscosity and good shear-thinning needed for hole cleaning and solids support

4. Low in mud tank

5. ~ 0 in hole when flow interrupted

Rheology Control in Drilling Fluids

- All properties influenced by mud type and condition
  - Plastic viscosity influenced by solids content
  - Yield point influenced by chemical environment

- In OBM, there are contributions to rheology from:
  - Rheology additives (organoclays, polymeric viscosifiers) affect $PV$ and $YP$
  - Dispersed solids (weight material, drill cuttings) affect $PV$
  - Emulsified brine phase affects $PV$

- In addition
  - Treatment of brine phase in OBM can increase droplet rigidity and modify its surface chemistry, leading to enhancement of LSR rheology
  - Use of surface treated, micro-fine weight material can impart steric stabilisation to suspension, thus reducing dependence on LSR rheology for solids suspension and sag mitigation.
Brine Phase Treatment in OBM

- Brine viscosifiers can improve LSR rheology
- They can show synergistic effect with some oil-phase viscosifiers
- Improved LSR rheology reduces settling of weight material

Treated Micro-Fine Barite vs. API Barite

- Comparison of particle size distributions
- Treated micro-fine barite creates lower rheology than conventional OBM of same mud weight
- Steric stabilisation improves resistance to settling

Comparison of rheology profiles at 82°C and 5000 psi for 1.32-SG fluids
Effect of Temperature on Rheology

- Drilling fluids are exposed to a wide range of temperatures
  - In deepwater drilling temperatures can range from ~ 4°C at seabed to well above 100°C downhole.
- This places major demands on fluid rheology:
  - Maintain low HSR viscosity at low temperatures in order to reduce pumping pressures
  - Provide adequate LSR rheology at high temperatures to suspend solids and reduce barite sag downhole.
  - A tough challenge to meet for conventional fluids
- One solution is a synthetic-based invert emulsion fluid, which
  - uses high-performance polymeric additives, a small amount of organoclay particles, and emulsifiers
  - generates a temperature-stable rheology over the range frequently encountered in deepwater drilling (4-120°C).

**HTHP Rheology**

- The HTHP rheology of drilling fluids is important for their performance downhole
- High-temperature gelling can occur as a result of
  - breakdown of additives
  - interaction of products
- HTHP rheology is characterised in Fann 70 or 75 viscometers which allow measurements at up to 250°C and 1360 bar.

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Press. (b)</th>
<th>YP (lb/100 ft²)</th>
<th>Gel 10 min (lb/100 ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>0</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>114</td>
<td>2</td>
<td>15</td>
<td>3</td>
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<tr>
<td>118</td>
<td>4</td>
<td>18</td>
<td>4</td>
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<td>123</td>
<td>6</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>127</td>
<td>8</td>
<td>22</td>
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<tr>
<td>131</td>
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<td>135</td>
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<tr>
<td>159</td>
<td>24</td>
<td>38</td>
<td>24</td>
</tr>
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</table>
• In some drilling fluid systems, clay particles with surface charge, or cross-linkable polymeric materials, form a gel that helps support the weight material and drill cuttings.

• At higher shear rates the network breaks down and the fluid flows with low viscosity.

• This thixotropic characteristic is an optimal type of rheology for conventional drilling fluids

  - Provided that the time scales for buildup and breakdown of structure are small

\[
\frac{d\lambda(t)}{dt} = a[1 - \lambda(t)] - b\lambda(t)\dot{\gamma}
\]

\[
\tau(t) = \lambda(t)\tau_y + [\mu_c + c\lambda(t)]\gamma^n
\]
Hole Cleaning

- Removing cuttings from the wellbore during drilling is an essential function of the drilling fluid.
- Hole cleaning is difficult in long, inclined, tangent sections due possible accumulation of cuttings beds on the low side of the hole.
- Possible consequences of poor hole cleaning:
  - reduced rate of penetration
  - high torque
  - stuck pipe
  - lost circulation
  - difficulties running and cementing casing

Factors Affecting Hole Cleaning

<table>
<thead>
<tr>
<th>Mud: flow rate</th>
<th>Cuttings: size</th>
</tr>
</thead>
<tbody>
<tr>
<td>rheology</td>
<td>density</td>
</tr>
<tr>
<td>density</td>
<td>shape</td>
</tr>
<tr>
<td></td>
<td>stickiness</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Hole: ROP</th>
<th>Drillpipe: diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>size</td>
<td>eccentricity</td>
</tr>
<tr>
<td>quality</td>
<td></td>
</tr>
</tbody>
</table>
Role of Rheology in Hole Cleaning

- To transport the particle out of the inclined section before it settles out we must have:
  \[ T_s \gg T_T, \quad \text{or} \quad \frac{D}{V_s} \gg \frac{L}{V_T} \]

- \( V_s \) can be estimated from Stokes' settling velocity:
  \[ V_s = \frac{\Delta \rho g d^2}{18 \mu} \]

- Giving:
  \[ \mu \gg \frac{L d \Delta \rho g}{DV} \frac{18}{18} \]

  For:
  \[ V_T = 1 \text{ m/s} \quad L = 1000 \text{ m} \]
  \[ D = 20 \text{ cm} \quad d = 1 \text{ mm} \]
  \[ \Delta \rho = 1200 \text{ kg/m}^3 \quad g = 10 \text{ m/s}^2 \]

  \[ \mu \gg 3.3 \text{ Pa} \cdot \text{s (3300cP)} \]

What Shear Rate?

- For non-Newtonian fluids, viscosity is a function of shear rate.

- Effective shear experienced by the particle is net of those due to translational and gravitational flows, but, the dominant component is due to flow
  \[ \dot{\gamma} = \frac{4V_T}{w} \quad (w \text{ is width of annulus}) \]

- For \( V_T = 1 \text{ m/s} \) & \( w = 5 \text{ cm} \), shear rate is; \( \dot{\gamma} = 80 \text{ s}^{-1} \) (47 rpm on Fann 35)

- Fluid with 3.3 Pa-s viscosity at 80 s\(^{-1}\) has a shear stress of 264 Pa, equivalent to a Fann value of 550 lb/100 ft\(^2\)
  - An unrealistically high value for drilling fluids

- Thus, rheology alone cannot be utilised to prevent particle settling during flow
Can Rheology Prevent Settling in Stationary Fluid?

- To prevent settling when flow is interrupted, the gravitational force must be balanced by viscous forces:

\[ \tau_v \times 4\pi \left(\frac{d}{2}\right)^3 = \frac{4}{3} \pi \left(\frac{d}{2}\right)^3 \Delta \rho g \]

- For the 1-mm particle with \( \Delta \rho = 1200 \text{ kg/m}^3 \):

\[ \tau_v = 2 \text{ Pa} \]

- This is “true” yield stress.

- Based on Zamora, et al.’s analysis, the required YP would be 4 - 10 Pa. This gives a realistic range of 8 - 20 lb/100 ft² for YP.

Mud Flow Regime Options

**Turbulent**
- Most efficient for hole cleaning
- Prevents formation of cuttings beds and disturbs/re-suspends any cuttings beds which do form
- Can erode weak formations
- Pump capacity may be limiting factor
- Gives large pressure drops (can use drag reducers)

**Laminar**
- Carries cuttings effectively but does not easily re-suspend cuttings beds
- Cuttings beds transported by sliding and saltation
- Hole cleaning can be augmented by low viscosity pills and drill pipe rotation

**Plug**
- Fluids in plug flow give good hole cleaning in large holes at low pump rates
- Examples are MMO/MMH and polymer muds with high (>2 ppb) concentrations of Xanthan gum
- Fluids have low PV, high YP and high, flat gels
Barite Sag

- Sag is the settling of weight material under gravitational forces, leading to density segregation of the drilling mud
- Sag can occur
  - with any solid weight material; Barite, haematite, calcium carbonate, salt crystals
  - in both OBM and WBM, but is seen more often in OBM
  - over a wide density range (1.4 – 2.4 s.g.)
  - through Dynamic and/or Static settling
- Can result in variations up to 0.5 s.g.
- Is observed in circulating fluid after a static period

Barite Sag

- Sag is more problematic in deviated wellbores where:
  - gravity induced settling forms density gradient or barite bed on low side of hole
  - barite beds can slide down the low side of the hole (depends on hole angle and strength of bed), further increasing the density contrast in the hole, a process known as the “Boycott Effect”
- Problems caused by sag
  - Poor control of bottom-hole pressure
    - inhomogeneous mud weight
    - fluctuations in the equivalent circulating density
    - induced fractures (lost circulation problems)
    - possible influx of formation fluids (well control problems)
  - wellbore instability
  - Problems while tripping & running casing
  - Stuck pipe & logging tools
  - Poor cement placement
Techniques to Study and Measure Sag

  - method based on Fann viscometer (VST)
  - static/dynamic & up to 85°C
  - variable inclination coaxial cell - inner reciprocator
  - static & dynamic sag
  - Measures dynamic sag


- Measurements at 50°C
- Solid lines represent polymeric OBM viscosifiers
- Markers represent organoclay viscosifiers
Effect of Rheology Additives on OBM Rheology

- Measurements at 50°C
- OB2: hydrophobically modified bentonite
- OA2: hydrophobically modified attapulgite
- P5/2: diblock styrene-ethylene/propylene copolymer

Effect of LSR Viscosity on Dynamic Sag

- Dynamic sag measured by VST + sag-shoe method at 50°C
- Viscosity at 10⁻² s⁻¹ and 50°C
- Clay and polymeric additives

G' measured at 1 Hz and 20°C
Effect of $\tan \delta$ on Dynamic Sag

- $\tan \delta = G''/G'$
- $\tan \delta$ at 1 Hz and 20°C

- $V^* = (G'^2 + G''^2)^{1/2} / 2\pi f$
- Complex viscosity at 5 Hz and 20°C

Conclusions

- Drilling fluids are complex, multi-component suspensions and emulsions designed to perform a variety of functions during the drilling operation.
- The continuously changing environment to which the fluids are exposed means that their properties must be monitored and controlled throughout the drilling operation.
- Rheology is a key parameter that affects many functions of drilling fluids, e.g. friction pressure, hole cleaning, barite sag, etc.
- Low HSR viscosity favours the hydraulics of the drilling operation, while sag prevention and hole cleaning benefit from high LSR rheology.
- Thus, the optimum conventional fluid is one which has thixotropic characteristics with short structure breakdown/buildup time scales.
- Novel fluids are now available which use steric stabilisation to reduce dependence on LSR rheology for sag prevention and hole cleaning.