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Chapter

Perspective Chapter: Rheological Considerations for Drilling and Enhanced Oil Recovery Fluids

Nnaemeka Uwaezuoke

Abstract

Screening of models to determine the applicability based on absolute average error is an acceptable approach. It is an appropriate model that guarantees greater accuracy in hydraulic computations. An improperly performed hydraulic calculation would cause poor hole cleaning and drilling cost overrun due to excess rig time. Also, due to inhibiting factors such as gravity, viscous and capillary forces; enhanced oil recovery had been adopted as an alternative mechanism to aid flow in the reservoir. An approach to rheological parameters and model selection is presented. Underlying mechanisms and considerations in the technology of enhanced oil recovery are presented. Rheology of drilling fluid is considered for effective hole cleaning, adequate cuttings suspension, averting barite sag, and prevention of excessive pipe surge and swab pressures. Similarly, the rheological characteristics of enhanced oil recovery fluids are monitored to retard pore blocking and prevent polymer loss during the fluid injection process. Understanding the rheology at a low shear rate range of $0.1-100 \text{ s}^{-1}$ of enhanced oil recovery fluids was highlighted. Advanced rheology equipment, viscoelastic behavior, nano-rheology, and smart fluids are matters of attention.

Keywords: absolute average error, generalized reduced gradient, enhanced oil recovery, rheological parameters, SOLVER®, viscous forces, viscoelastic behavior

1. Introduction

Complex fluids such as solid-liquid (suspensions), liquid-gas (foams), solid-gas (granular), and liquid-liquid (emulsions) are often encountered in the field of material science. The rheology of these structured and polymeric materials is determined by their molecular chemistry. Whereas intramolecular forces within the polymers control the rheological behavior, the interactions of constituents are the determinants of rheological characteristics.

A wide-scale scope of application of rheology was projected in the early twentieth century when its current definition was accepted by the American Society of Rheology [1]. Subsequently, advances have been made in the fields of polymer, suspension, and bio-rheology. Rheology is affected by shear rate, pressure, temperature, molecular weight, and concentration. The future of rheology and its applications had been
envisioned to include fluid blends, nano-rheology, smart fluids, and viscoelasticity measurements [2]. However, polymer rheology is dominant in rheological literature. Polymeric substances have found wide applications in drilling fluid formulations and enhanced oil recovery processes.

Nonetheless, the subject of drilling optimization is well explored. Recently, reference models for benchmarking in production and drilling optimization have been presented [3]. They include the application of metrics such as hole cleaning, rate of penetration, well trajectory, minimum specific mechanical energy, well placement, and bottom hole assembly placement. Controllable parameters considered most important to yield minimal drilling cost are usually treated mathematically [4]. At the center of the hole, the cleaning metric is drilling fluid and factors attributable to it. Its rheology has often been defined by the rheological parameters. They include flow behavior index (n), consistency factor (k), gel strength, and yield shear stress ($\tau_y$). They are vital in the formulation and monitoring of drilling fluids. They are also considered in control of fluid functions during treatment. Whereas the flow behavior index helps to determine the deviation from Newtonian behavior and the degree of non-Newtonian characteristics, the consistency factor defines the degree of viscous properties for similar viscous fluids. In other words, it serves as a pointer to which fluid is more viscous than the other. The yield stress provides a guide as to the start of the pseudoplastic flow.

Similarly, an oil reservoir can flow to the surface using its natural energy. This is known as primary recovery. At a stage in the life of the reservoir, it might become suitable to support this energy by using external fluid for continued production to be possible by injection of water or gas. This is known as secondary recovery; where the fluids are injected directly into the reservoir to repressurize it. It is often convenient to inject gas into the gas zone and water into the water zone within the reservoir rock. Irrespective of these conventional approaches, only about one-third of the initial oil-in-place is produced. However, in completed and producing wells, the existence of gravity, viscous and capillary forces within the reservoir make complete production of the hydrocarbons such as crude oil in the reservoir a challenge. In an oil and gas reservoir, the capillary force squeezes hydrocarbon through the small pore spaces within the rock matrix known as the pore throat. By its size, number, and distribution, other flow and resistivity characteristics of the rock are controlled by the pore throat. Capillary pressure works against interfacial tension between fluid phases in the reservoir. Its influence is greater in smaller pore diameters. Similarly, gravity forces are vertically directed and are attributable to density contrast between the fluids. Gravity forces have been considered to have a huge effect during primary recovery. The gravity process can occur in the form of free gravity drainage and forced gravity drainage processes. The former is prevalent in high permeability reservoirs [5]. It is also observed in reservoirs with adequate oil layer thickness at levels of low pressure. In contrast, forced gravity drainage is observed in dual porosity reservoirs where gas proceeds to the area of higher permeability leaving oil in low permeability areas. Pressure difference provides force to drive gas and displace oil. Also, viscous forces are a representation of fluid flow due to pressure gradients given by Darcy’s law. The law governs the flow of gas, oil, and water in a porous media [6]. The enhanced oil recovery techniques have been in use since the remaining resource of about two-thirds could be commercially viable. The objective of the tertiary technique is to alter the properties of the reservoir fluids [7]. Miscible displacement, chemical flooding, and thermal and microbial flooding processes are common. Polymer flooding, which is a chemical flooding system is one of the most promising enhanced oil recovery techniques.
techniques [8–12]. Whereas miscible displacement and chemical flooding are used in reservoirs with light crude oils, thermal processes are used in reservoirs with heavy crude oils and microbial processes use microorganisms to assist in oil recovery. The rock and fluid, as well as other physical properties, control the choice of the method to apply. In other words, enhanced oil recovery techniques’ target is to reduce residual oil. However, the rheology of the displacement and displaced fluids are factors considered during the process. Viscosity is a fluid property; hence, contributes appreciable influence on recovery. Sweep efficiency is a measure of the effectiveness of an EOR process. It is dependent on the volume of the reservoir contacted by the reservoir fluid. Whichever fluid displacement process is in use, the overall recovery efficiency, $E$, is determined by the product of volumetric (macroscopic) and microscopic displacement efficiencies, $E_v$ and $E_d$, respectively. $E_v$ is a measure of contact between displacing fluid and oil-bearing reservoir while $E_d$ is a measure of how good the residual oil has been mobilized by the displacing fluid once in contact with the oil. Volumetric sweep efficiency depends on reservoir fractures, injection pattern, the position of fluid contacts, off-pattern wells, reservoir anisotropy, flow rate, mobility ratio, reservoir thickness, and displacing and displaced fluids density difference. Moreover, $E_v$ is a result of the product of two terms; the pattern areal ($E_a$) and vertical ($E_v$) sweep efficiencies (Figure 1). Several factors affect $E_v$ and $E_d$. They include; for macroscopic displacement efficiency (i) heterogeneities and anisotropy, (ii) rock matrix type where the oil is found, (iii) mobility of displacing fluids relative to the displaced fluids, (iv) production and injection wells arrangement pattern, and (i) capillary pressure, (ii) relative permeability, (iii) surface and interfacial tension, and (iv) wettability for microscopic displacement efficiency.

Mobility is the relative measure of ease of flow of fluid through a porous media. Apparent mobility is defined as the ratio of effective permeability to the fluid phase viscosity. Similarly, the mobility ratio, $M$, is a measure of relative apparent mobilities in a displacement process. Hence,

$$\lambda = \frac{k_{o,g,w}}{\mu_{o,g,w}} \quad (1)$$

The mobility of oil, gas, and water is given as;

$$\lambda_o = \frac{k_o}{\mu_o} = \frac{k_{e,o}}{\mu_o} \quad (2)$$

Figure 1. Schematic of volumetric sweep components: (a) areal sweep and (b) vertical sweep in stratified formation.
When water is the displacing fluid and oil is the displaced fluid (water flooding),

\[ M = \frac{K_{rw}}{K_{ro}} \frac{\mu_o}{\mu_w} \]  

(6)

Where \( k_o \), \( k_g \), and \( k_w \) are the effective permeability to oil, gas, and water, respectively; \( k_{ro} \), \( k_{rg} \), and \( k_{rw} \) are the relative permeability to oil, gas, and water, respectively, and \( k \) = absolute permeability.

In summary, chemicals used in EOR are used to improve mobility ratio, alter the wettability, or lower interfacial tension between oil and water. A mobility ratio of unity or less causes efficient displacement of oil by water in a piston-like manner [13]. In contrast, if the mobility ratio is greater than unity, fingering more mobile water through the oil would leave regions of upswept oil behind (Figure 2). It is a fundamental and most difficult interfacial instability to control [14]. In other words, a mobility ratio of less than unity is essential to avoid viscous fingering. Rheology study is basically a method of evaluation of enhanced oil recovery chemicals. This study would focus on rheology as there are other evaluation techniques such as the use of wettability alteration, interfacial tension, and core flooding experiments.

2. Background
2.1 Rheology of drilling fluids

Rheology tests carried out every twelve hours on drilling fluids include viscosity, gel strength, and yield stress. Viscosity is probably the most important of any material property as regards response to forces [1]. It is affected by variables such as pressure.

Figure 2.
Typical mobility ratio of (a) water-flooding process \((M>1.0)\), (b) polymer flooding process \((M\leq1.0)\).
and temperature. Viscosity decreases with temperature increase and pressure decrease for all liquids. The tests are better carried out with multispeed viscometers. The dial readings of the viscometer are analyzed to read the rheological parameters. Automatic calculations of model parameters are available in some instruments. Depending on the type of meter, typical precisely regulated test speeds are given in Table 1 [15–17]. The speeds could be manually, or computer controlled, enabling readings at a shear rate of up to 1000 rpm (1703 s\(^{-1}\)) for Type 1 viscometers.

One of the results of the analysis is the flow behavior index. Its value determines the velocity profile in the pipe or annular flow. Also, flow models such as laminar and turbulent flow regimes governed by viscous and inertial properties of the fluid respectively, are distinguishable from rheological models such as Newtonian, Bingham plastic, and pseudoplastic models [18]. Pseudoplastic fluids do not have a yield point. Yield point approximations such as those from 3 rpm dial reading and extrapolation of high shear stress readings back to the axis are not uncommon. The result would appear as a yield point similar to Bingham plastic, hence, pseudoplastic. However, the SOLVER\(®\) algorithm is a recommended approach for rheological parameters optimization [19, 20]. Drilling fluid rheology-related problems include poor hole cleaning, barite sag, suspension, and excessive surge and swab pressures [21]. Surge pressure is a temporary bottom-hole pressure increase due to downward pipe movement. It can cause the fracture pressure limit of formation to be exceeded leading to lost circulation. Conversely, swab pressure is a bottom-hole pressure decrease that can cause well kick due to hydrostatic pressure reduction.

<table>
<thead>
<tr>
<th>Test speeds, rpm (s(^{-1}))</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
<th>Type 5</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>600 (1021.8)</td>
<td>600 (1021.8)</td>
<td>600 (1021.8)</td>
<td>600 (1021.8)</td>
<td>600 (1021.8)</td>
</tr>
<tr>
<td>2</td>
<td>300 (510.9)</td>
<td>300 (510.9)</td>
<td>300 (510.9)</td>
<td>300 (510.9)</td>
<td>300 (510.9)</td>
</tr>
<tr>
<td>3</td>
<td>200 (340.6)</td>
<td>200 (340.6)</td>
<td>200 (340.6)</td>
<td>200 (340.6)</td>
<td>200 (340.6)</td>
</tr>
<tr>
<td>4</td>
<td>100 (170.3)</td>
<td>180 (306.54)</td>
<td>100 (170.3)</td>
<td>100 (170.3)</td>
<td>100 (170.3)</td>
</tr>
<tr>
<td>5</td>
<td>60 (102.18)</td>
<td>100 (170.3)</td>
<td>60 (102.18)</td>
<td>60 (102.18)</td>
<td>6 (10.22)</td>
</tr>
<tr>
<td>6</td>
<td>30 (51.09)</td>
<td>90 (153.27)</td>
<td>30 (51.09)</td>
<td>30 (51.09)</td>
<td>3 (5.11)</td>
</tr>
<tr>
<td>7</td>
<td>20 (34.06)</td>
<td>60 (102.18)</td>
<td>20 (34.06)</td>
<td>6 (10.22)</td>
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</tr>
<tr>
<td>8</td>
<td>10 (17.03)</td>
<td>30 (51.09)</td>
<td>10 (17.03)</td>
<td>3 (5.11)</td>
<td>—</td>
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<tr>
<td>9</td>
<td>6 (10.22)</td>
<td>6 (10.22)</td>
<td>6 (10.22)</td>
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<td>3 (5.11)</td>
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</tr>
<tr>
<td>11</td>
<td>2 (3.41)</td>
<td>1.8 (3.07)</td>
<td>2 (3.41)</td>
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<tr>
<td>12</td>
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<tr>
<td>14</td>
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<td>—</td>
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</tr>
<tr>
<td>15</td>
<td>0.2 (0.34)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>16</td>
<td>0.1 (0.1703)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Note: the type numbers stated in Table 1 are not necessarily in any order of importance, but for mere convenience.

Table 1. Precisely regulated test speeds in viscometers.
2.1.1 Laminar flow

This Laminar flow occurs when the individual flow layers (laminae) slide past one another with a minimum of mixing. Generally, laminar flow is the preferred annulus flow profile because it results in less pressure loss and reduces hole erosion. To achieve efficient cuttings transport in laminar flow, the fluid rheology should be tailored to give a flat velocity profile, with a small “n” value for Power-Law fluids. This avoids excessive cuttings slipping near the borehole wall and drill pipe.

2.1.2 Transitional flow

Transition flow occurs where the laminar flow can no longer exist due to the increased momentum forces as the fluid goes into turbulence as velocity further increases. This is sometimes referred to as “unstable turbulence.” However, a recent approach has been the application of critical velocity to distinguish the point of transition from laminar to turbulent flow regime. In this, if the average fluid flow velocity exceeds the critical velocity, the flow regime is considered turbulent, otherwise laminar.

2.1.3 Turbulent flow

Turbulent flow occurs when the fluid is constantly swirling and eddying as it moves through the flow channel. Pressure losses within a circulating system increase as the degree of turbulence increases. Additionally, in turbulence, the viscous properties of mud no longer affect cuttings removal efficiency. Only the momentum forces of a mud, that is density and predominantly velocity, affect hole cleaning in a turbulent flow. In turbulent flow, the fluid velocity at the walls is zero; however, the velocity profile within the stream is essentially flat. This flat profile improves hole cleaning characteristics but, at the expense of increased pressure losses through fluid turbulence. A highly turbulent flow may also erode a soft formation (washout) which can reduce cuttings removal efficiency, increase cementing volumes, prevent zonal isolation, and affect wireline log quality. Generally, the turbulent flow should be avoided if possible.

2.2 Rheology of enhanced oil recovery fluids

The rheology of enhanced oil recovery fluids is essential to make the correct selection of the fluid that would yield maximum recovery. Enhanced oil recovery fluids’ rheology must be measured, evaluated, and understood over a wide range of shear rates likely to be encountered during injection operations. “Various rheological models have been used to describe the properties of non-Newtonian gelling agents” [22]. A report has been presented on the effects of shear thinning, shear thickening, and viscoelastic substances on enhanced oil recovery [23]. The results indicated that the fluids enhanced production to different degrees. It signifies the need to properly screen available enhanced oil recovery fluids based on rheological behavior. For instance, reservoir screening criteria in EOR for polymer flooding consider reservoir properties [24], with the average and range of values shown in Table 2.

However, a lot of research on several substances for enhanced oil recovery has been published [23, 25–27]. Nanoparticles have also been applied. Particularly, hydrogel and surfactant polymers have been shown to enhance oil recovery [28–30].
improve displacement efficiency and recovery. Usually, they are used with alkali agents and surfactants to increase sweep efficiency. However, the hydrogel polymer is used to increase the viscosity of water-containing fluids. Polymers are added to increase the viscosity of displacing fluid and reduce the mobility ratio. They also result in a stable front, preventing fingering and the formation of channels. This increased viscosity reduces the fluid's flow rate relative to the oil. This results in increased oil production. Hydrolyzed polyacrylamides and biopolymers which are high molecular weight and solution concentration polymers are commonly used. They exhibit viscoelastic, non-Newtonian, and shear-thinning behavior. Due to their viscoelastic properties, they can dissipate or store energy. When they are transported through pore narrow connecting channels, they accelerate and decelerate to maintain a constant flow rate because they exhibit high extensional viscosity. Both synthetic and biopolymers are used due to these characteristics. However, synthetic polymers are preferable due to temperature tolerance, salinity, and cost. In terms of performance, it has been reported that polymer fluids that exhibited shear thinning/thickening characteristics such as HPAM resulted in significantly higher oil recovery compared with a fluid that exhibited only shear thinning behavior such as Xanthan which is a biopolymer [31]. Similarly, in an experiment on the rheology of polymer solutions for polymer flooding, the shear rate range of \(0.1–100 \text{ s}^{-1}\) (\(\leq 60 \text{ rpm}\)) was applied. It was considered that this range covered rates for injected fluid near the wellbore and into the reservoir away from the wellbore [32]. A range of \(0.1–10 \text{ s}^{-1}\) (\(\leq 6 \text{ rpm}\)) for rates into the reservoir was used. Similarly, a four-parameter model, the Carreau model, had been used to fit the relationship between viscosity and shear rate [33]. It was used above critical values of shear rate. The principal objectives of the study of the rheology of enhanced oil recovery fluids are (i) to prevent pore blocking and (ii) to prevent polymer loss. When these factors are under control, economic benefit and technical performance are guaranteed.

### 3. Advanced rheology

#### 3.1 Advanced rheology equipment

Of all the types of viscometers available such as capillary, falling ball, falling piston, orifice, rotational and vibrational viscometers, rotational viscometers are

<table>
<thead>
<tr>
<th>Reservoir property</th>
<th>Average or range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir type</td>
<td>Sandstone reservoirs are most preferred</td>
</tr>
<tr>
<td>&quot;Permeability&quot;</td>
<td>&quot;Average of 563 mD</td>
</tr>
</tbody>
</table>
| "Pore throat radius" | "
| Oil viscosity      | <30 cP |
| Reservoir temperature | 237.2°F |
| Formation water salinity | <10,000 ppm |
| Polymer concentration | 213 ppm |

Table 2. Reservoir properties for EOR.
commonly used in the oil and gas industry in drilling fluid and other measurements. They are not based on gravity but by the fluid internal shear stress measured by rotating a spindle immersed in the fluid whose rheological properties are desired. It works for both Newtonian and non-Newtonian substances. Rotational viscometers designed to provide data for all the twelve data points for the speeds presented in sub-section 2.1 and Table 1, it is referred to as twelve-speed viscometer. All the data points are collectively analyzed for low, medium, and high speeds. The results present a more accurate rheological behavior compared to when only two or six data points are used. However, it is standard oilfield practice to perform independent analysis with dial readings and compare with the rheological parameters automatically computed by the viscometer. Analyses of dial readings at low shear rates are desirable to monitor flow away into the reservoir from the wellbore during EOR and viscosity building capacity of mud at low shear rates for cuttings suspension.

Similarly, viscometers that take readings in high pressure and high-temperature conditions can enable drilling fluids to be evaluated under varying downhole conditions. Models such as Chandler Model 7600 for HPHT can measure at a speed range of 0–900 rpm, with temperature and pressure up to 600°F and 40,000 psig respectively.

Also, in-line rheometers offer real-time viscosity measurements. They reduce downtime and sampling cost. It is based on the analysis of the shape of the velocity profile and the shear stress distribution of flow in a cylindrical pipe. These inline meters should have the ability to take measurements in pressurized lines.

3.2 Viscoelastic behavior

Polymeric fluids are applied in drilling and EOR fluid formulations. The flow behavior of polymeric substances cannot be adequately described by viscosity alone [34]. During deformation, they exhibit viscous and elastic behaviors or both. In other words, they exhibit both shear thinning and shear thickening behaviors. For instance, viscoelasticity is important since the speed of fluid changes as it flows in the porous media. Polymers used in EOR have high molecular weight and concentration, hence, exhibiting viscoelastic behavior [35]. The applied stress gives an instantaneous strain. A viscous and time-dependent strain comes after. Similarly, in drilling fluid engineering, viscoelastic properties of an oil-based mud have been associated with its ability to perform better than a water-based mud in hole cleaning [36]. Viscoelastic properties include yield stress and linear viscoelastic range. In the linear viscoelastic range, there is a linear relationship between strain and stress. Viscoelastic and thixotropic behaviors are one of the greatest challenges for rheologists [37], both in theoretical description and experimental characterization.

3.3 Nanorheology

Nanoparticle shape, concentration, shear rate, magnetic field, and surfactant all affect the rheology of nanofluids. Both metallic and non-metallic nanoparticles can be used to build colloidal suspensions known as nanofluids. The density and viscosity of the nanofluid are altered which affects its rheology. Nanofluids that contain less than 13% in volume of nanoparticles behave like Newtonian fluids, whereas those that have concentrations above that threshold of NPs behave non-Newtonian. Similarly, it has been highlighted that nanofluids that contain spherical NPs have a greater tendency to behave Newtonian, whereas those containing nanotubes show non-Newtonian
behavior [38]. Also, it was observed that nanofluids show Newtonian behavior at low shear rates and behave non-Newtonian at high shear rates. Hence, the inclusion of NPs in EOR fluids can alter its rheology both within the well and deep into the reservoir. The concentration and shape of the NPs, together with the shear rate can be utilized to produce a fluid that can show shear thickening/shear thinning behavior which is desirable.

It might be deduced that the use of more than 13% in volume of NPs or nanotube-shaped NPs for non-Newtonian behavior, and injection at low shear rates for Newtonian behavior can produce shear thinning/shear thickening behavior for effective sweep efficiency for enhanced production of oil. Newtonian fluid behavior (Eq. (7)) is characterized by a constant viscosity that is independent of shear rate at a constant temperature. The constant viscosity, which might be achieved at a low shear rate, is required to maintain a stable flood front in EOR at the low shear rates. Then, with the less viscous displaced fluid (oil), \( M \leq 1 \), which prevents viscous fingering. Moreover, in drilling fluid formulations, the use of a higher concentration of NPs and nanotube NPs might guarantee shear thinning behavior. For improved viscosity at low shear rates for cuttings suspension and improved hole cleaning, concentrations lower than 13% in volume of NPs is desirable. The drilling fluid should have yield shear stress as a rheological parameter. However, the presence of NPs in both the drilling and EOR fluids tends to alter the temperature of the environments [39–41]. Ionanofluids research is also recent.

Surfactants are used to alter surface tension. Surfactant solutions exhibit ultra-low interfacial tension when salt and alkali are present. Hence, rock wettability is altered from an oil-wet to a water-wet state. Surfactant-polymer flooding can offer more than 28% additional oil recovery [42]. In summary, NPs can be used to engineer the rheology of drilling and EOR fluids.

### 3.4 Smart fluids

These are fluids whose properties can be altered by the application of an electric or magnetic field; thus, electrorheological (ER) and magnetorheological (MR) fluids can be formed. Other forms of smart fluids exist. In ER fluids, an electric field can be applied to alter the yield stress to change the fluid property. With this technique, the consistency of the liquid can be converted to a gel within a very short time interval and vice versa [43]. The rheological properties are electric field dependent [44] and they are often difficult to characterize [45]. The shear yield stress is electric field dependent, and the fluid can behave as a Bingham Plastic fluid. The electric field strength determines the yield point; hence, the viscosity can be controlled by the electric field adjustment. Since most ER fluids are liquid suspensions of metals or zeolites, the common problem is that they can settle out. An electric field can also be used to alter the surface tension in a fluid to create a smart fluid. This can be controlled by the use of NPs.

Similarly, in MR fluids, small magnetic dipoles suspended in a nonmagnetic fluid are used to increase the fluid property such as apparent viscosity. The magnetic particles are randomly distributed in suspension in a carrier fluid (oil). When the magnetic field is not applied, the fluid viscosity is low. In the presence of a magnetic field, the magnetic particles align themselves along the lines of magnetic flux to increase the viscosity [46]. MR fluids are not exactly Bingham Plastic but show viscoelastic behavior and shear thinning characteristics. An electric field can also be used to alter the surface tension in a fluid to create a smart fluid.
4. Rheological models and parameters selection

4.1 Rheological models

Rheology models are analyzed to determine the rheological parameters. Moreover, they are used to make predictions and perform hydraulics analysis. Several rheological models exist [33, 47, 48]. The model equations are given (Eqs. (7)-(17)).

4.1.1 Newtonian fluids

Examples of Newtonian fluids are water, gases, and high-gravity oils. In the drilling industry, viscosity is generally expressed in centipoises (cP), where 1 cP = 0.01 poise. At constant temperature and pressure, the shear rate and the shear stress are directly proportional. The constant of proportionality (μ) is the Newtonian viscosity. The rheological curve is a straight line that passes through the origin. The slope of the line is the Newtonian viscosity. The yield stress of a Newtonian fluid will always be zero. They will not suspend cuttings or weighting materials under static conditions—pumps off.

4.1.2 Non-Newtonian fluids

Most drilling fluids are too complex to be characterized by a single value for viscosity. The apparent viscosity measured for these fluids depends upon the shear rate at which the measurement is made and the shear rate history of the fluid. Fluids that do not exhibit a direct proportionality between the shear stress and the shear rate are classified as non-Newtonian. Non-Newtonian fluids that are shear rate dependent are classified as either pseudoplastic (shear thinning) or dilatant (shear-thickening). A fluid is pseudoplastic if its apparent viscosity decreases with an increasing shear rate. A fluid is dilatant if its apparent viscosity increases with an increasing shear rate. Drilling fluids (and cement) are generally pseudoplastic in nature and are termed shear-thinning because they tend to decrease in viscosity as the shear rate increases. Shear-thinning is a very desirable property for drilling fluids. It means that, at low shear rates or low pump rates, the fluid is more viscous and can suspend more drilled materials.

Most successful drilling fluids are non-Newtonian. They do not exhibit a linear relationship between shear stress and shear rate. The relationship depends on the viscosifier. The effective viscosity (also called equivalent or apparent viscosity) decreases as the shear rate increases. Within that group are several general types and rheological mathematical models to describe them. Similarly, non-Newtonian fluids that have yield stress that varies with time are thixotropic if the apparent viscosity decreases with time after the shear rate is increased to a new constant value or rheopectic if the apparent viscosity increases with time after the shear rate is increased to a new constant value. Typically, drilling fluids (and cement slurries) are thixotropic.

The Bingham and Power Law rheological models approximate the pseudoplastic behavior of drilling fluids.

4.1.3 Bingham Plastic rheological model

A Bingham plastic will not flow until the applied shear stress (τ) exceeds a certain minimum value (τ_y), called the yield point stress (YP). When the yield stress is
exceeded, changes in the shear stress are proportional to changes in the shear rate, and the constant of proportionality is called the plastic viscosity (PV or $\mu_{pl}$). The yield point is a measure of the electrical attractive forces in the mud under flowing conditions. The units are the same as the units for the Newtonian or apparent viscosity. The apparent viscosity or effective viscosity, defined as the shear stress divided by the shear rate varies with the shear rate for non-Newtonian fluids. The apparent viscosity is the slope of the line from the origin to the shear stress at a given shear rate. It decreases with increasing shear rate; therefore, Bingham plastics are shear thinning. As the shear rate approaches infinity, apparent viscosity reaches a limit (the PV) and is the slope of the Bingham plastic. The Bingham Plastic model is still used extensively in the drilling industry but does not accurately represent drilling fluids at low shear rates and yield behavior is greatly overestimated.

4.1.4 Power Law model

The Power Law rheological model also requires two parameters to define the relationship between the shear rate and the shear stress. The consistency factor describes the thickness of the fluid and is analogous to the apparent viscosity. As the consistency factor increases, the drilling fluid is expected to be more viscous. The flow behavior index indicates the degree of non-Newtonian behavior. When $n = 1$, the Power Law is identical to the Newtonian model (viscosity does not change with shear rate). If $n > 1$, the fluid is dilatant (e.g. quicksand) or shear thickening. If $n$ is less than unity, the fluid is pseudoplastic or shear-thinning (the apparent (effective) viscosity decreases as the shear rate increases). The flow behavior index is 0.3–0.8 for most successful drilling fluids. If $n > 1$, it is not a good idea for drilling fluid (apparent or effective viscosity increases with shear rate). Characteristics of this fluid are no yield points. Although the Power Law more accurately represents the behavior of drilling mud at low shear rates, it does not have yield stress; therefore, the Power Law can provide inaccurate results at very low shear rates. In general, a drilling fluid has both yield stress and shear-thinning behavior. At high shear rates, all of the models represent the fluid behavior reasonably well. A typical drilling fluid tends to behave somewhere between the Power Law behavior and a Bingham fluid. The Herschel-Bulkley model is a typical example and combines Power Law and Bingham Models.

4.1.5 Herschel-Bulkley model

This model is probably the most complete model currently in use. It is sometimes referred to as yield-pseudoplastic because it encompasses both the yield behavior of a non-Newtonian fluid and also allows for shear-thinning. The characteristics of the fluid include possession of yield points and shear thinning. Because these models are suitable for one type of fluid or another, the determination of a suitable model for a drilling fluid becomes necessary. This could be achieved by a statistical approach, by the use of the absolute average error.

Newtonian model: $\tau = \mu \gamma$  
Bingham plastic model: $\tau = \tau_y + \mu_{pl} \gamma$  
Power law model: $\tau = k \gamma^n$  
Herschel – Bulkley model: $\tau = \tau_y + k \gamma^n$
where \( \tau = \) shear stress, \( \gamma = \) shear rate, \( n = \) Power law index, \( \mu = \) Newtonian viscosity, \( \tau_y = \) yield stress, \( k = \) consistency factor, \( \mu_p = \) plastic viscosity, \( A \) and \( B = \) rheological parameters, \( C = \) correction factor applied to shear rate, \( \eta = \) steady-shear viscosity, \( \eta_0 = \) zero-shear-rate viscosity, \( \eta_\infty = \) limiting Newtonian viscosity at the high shear limits, \( \lambda = \) time constant, \( n - 1 = \) slope of \( \left[ \frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} \right] \) versus \( \gamma \) in log-log plot, \( d\nu/dr = \) shear rate gradient, \( C_H = \) rheological parameter in the Vom Berg and Hahn-Eyring models \( [s^{-1}] \), \( D = \) rheological parameter in the Vom Berg and Hahn-Eyring models \( [Pa] \), \( E = \) rheological parameter in the Hahn-Eyring model, \( \tau_c \) and \( \mu_c \) are yield stress and plastic viscosity of Casson model.

As shown, the models have two, three, or four rheological parameters. The ease of accurate calculation of rheological parameters increases for models with fewer rheological models. However, steps for the determination of optimized values of the parameters are presented in a published work [47] by the use of the SOLVER® algorithm. Other empirical methods are also available [49]. It was highlighted that the model that produces the least absolute average error should be selected. Another factor that determines the model to select in the model selection process is the ease of determination of the rheological parameters. It was pointed out that though the Robertson-Stiff yield point model gave lower absolute average error values, Herschel-Bulkley (yield Power Law); a three-parameter model was selected. The reason had to do with the ease of computation of the parameters. Regression and statistical software might be used to determine the parameters.

However, for any method chosen, a flow behavior index, \( n \), of unity signifies a Newtonian fluid behavior. Conversely values greater than one show dilatant (shear-thickening) fluid behavior. Also, flow behavior index values less than one denote pseudoplastic (shear thinning) fluid behavior. When the consistency factor, \( k \), is determined, it is a direct indicator of the degree of viscous behavior. The higher the value, the more viscous property the fluid is expected to exhibit. The yield shear stress, \( \tau_y \), would signify the start of pseudoplastic behavior. This might be referred to as the yield point stress of the fluid.

4.2 Rheological model selection and parameters optimization

4.2.1 SOLVER® iteration and optimization tool

To use SOLVER®, a model of the decision problem that specifies the following is built; (i) the measure to optimize, called the objective (ii) the decisions to be
made, called decision variables (iii) any logical restrictions on potential solutions, called constraints. It would find values for the decision variables ($\tau_y$, $n$, and $k$) that satisfy the constraints while optimizing (maximizing or minimizing) the objective (Figure 3). It changes the decision variables (iteration) as many times as possible to make the squared sum (SS) error between the data and the fit as small as possible. It does that with all the data points, trying to minimize them (constraints) while trying to make the SS error as small as possible using the generalized reduced gradient technique. The constraint precision and generalized reduced gradient convergence could be adjusted using the options tab.

5. Case study demonstration: model selection

5.1 Case study I

An additive has been verified as a viscosifier in water-based muds and used to prepare a mud formulation for use in a sandstone reservoir. Given in Table 3 are Fann viscometer readings (measured) from the mud sample determined by the use of the American Petroleum Institute (API) standard test procedures [50] taken at ambient temperature. The rheological parameters for Power Law (PL) and Herschel-Bulkley (HB) models are provided in Table 4. Propose a model suitable for hydraulic calculations for the mud? Provide the reason for the choice of model.
The results are summarized in Table 5 and plotted in Figure 4. Herschel-Bulkley model was selected because it has a lower absolute average error value.

Note: For the sample question, the rheological parameters have been provided.

Times always occur when an engineer is expected to determine the rheological parameters using all the six data points.

5.2 Case study II

The dial readings from a six-speed viscometer taken at ambient temperature have been provided in Table 6. Analyze the data and propose rheological parameters that represent the flow behavior and attempt to find a suitable model for the prediction of the characteristics of the fluid formulation.
Figure 5 is rheograms of viscometric readings while Figure 6 is the log-log graph. The equation shown as insert (Figure 6) is non-linear. From Figure 6, it could be observed that $n = 0.4885$ and $k = 2.6487$ lb.Sec$^n$/100 ft$^2$.

To get the yield stress, if the fluid is a Herschel-Bulkley fluid, Versan and Tolga’s [51] approach could be applied. Alternatively, the 3 rpm reading could be used as the yield stress. If it is a Bingham Plastic fluid, a formula could be used or intersect the graph. Both yield different results as shown in Table 7. Figures 7–9 show the plots for comparison.

![Figure 4](image1.png)

**Figure 4.**
Rheograms for three models combined.

<table>
<thead>
<tr>
<th>RPM</th>
<th>600</th>
<th>300</th>
<th>200</th>
<th>100</th>
<th>6</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dial Readings</td>
<td>75</td>
<td>58</td>
<td>47</td>
<td>32</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

**Table 6.**
Viscometer dial readings.

![Figure 5](image2.png)

**Figure 5.**
Rheogram of viscometric readings.
**Figure 6.**
Log-Log graph with power equation showing $k$ and $n$.

$y = 2.6487x^{-0.4885}$

**Figure 7.**
Rheogram of viscometric and HB model from SOLVER®.

<table>
<thead>
<tr>
<th>Approach used</th>
<th>Log-Log SOLVER® without Versan and Tolga YP</th>
<th>SOLVER® with Versan and Tolga YP</th>
<th>3 rpm Bingham Equation</th>
<th>Bingham Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB parameters</td>
<td>$n$</td>
<td>0.4885</td>
<td>0.4865</td>
<td>0.5284</td>
</tr>
<tr>
<td></td>
<td>$k$, lb.sec$^{-n}$/100 ft$^2$</td>
<td>2.6487</td>
<td>2.6297</td>
<td>2.0289</td>
</tr>
<tr>
<td></td>
<td>YP, lb/100 ft$^2$</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>BP parameters</td>
<td>YP, lb/100 ft$^2$</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>PV, cP</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

**Table 7.**
Summary of results.
5.3 Yield stress determination

The SOLVER® regression algorithm for the determination of the yield stress yields consistent results [47]. Eqs. (18)–(20) are applicable for yield point stress determination.

\[
\tau = \frac{\tau^* - \tau_{\min} + \tau_{\max}}{2 * \tau^* \tau_{\min} \tau_{\max}} \tag{18}
\]

\[
\gamma^* = \sqrt{\frac{\gamma_{\min}}{\gamma_{\max}}} \tag{19}
\]

Therefore,
\[ \gamma^* = \sqrt{\gamma_{\text{min}} \gamma_{\text{max}}} = 72.25 \text{ sec}^{-1} \]  

(20)

The corresponding value of shear stress \( \tau^* \) is determined by interpolation. The value is 17.30 lb/100 ft\(^2\). Therefore,

\[ \tau = \frac{\tau^* \tau_{\text{max}} - \tau_{\text{min}} \tau_{\text{max}}}{2 \tau^* - \tau_{\text{min}} - \tau_{\text{max}}} = 3.25 \text{ lb/100ft}^2 \]

(ii) A suitable model for the mud is chosen after the values of absolute average error between measured and model data have been determined. The \( E_{\text{AA}} \) for Herschel-Bulkley and Bingham Plastic models are 0.12974 and 0.19551 respectively. Hence, the HB model could be said to be a suitable model since it has a lower value for the \( E_{\text{AA}} \). All hole cleaning and hydraulics calculations should be based on the associated HB model parameters and correlations.

6. Summary

Drilling and enhanced oil recovery fluids designs are tailored to optimize rheological properties and parameters that include viscosity, gel strength, yield point, flow behavior index, and consistency factor. Rheology of drilling fluid formulations for oil and gas well drilling operations is considered for effective hole cleaning and adequate cuttings suspension when drilling (pump) is interrupted. Others include averting barite sag and prevention of excessive pipe surge and swab pressures. Similarly, the rheological characteristics of enhanced oil recovery fluids are monitored to retard pore blocking and prevent polymer loss during the fluid injection process. A low shear rate viscosity value is important in both drilling and EOR fluids. During drilling activity, it is the laminar flow regime that dominates flow in the wellbore-pipe annulus. The flow condition is desirable because a turbulent flow regime is considered to encourage borehole wall erosion and it places an upper limit on allowable flow conditions. Also, turbulent flow causes excessive pressure loss. With drilling fluids, the viscosity at low shear rates encountered in the annulus in the laminar flow regime has to be sufficient to suspend cuttings and enhance hole cleaning. Moreover, in enhanced oil recovery during fluid injection, the flow out of the wellbore into the reservoir is rather slow. The desire would be to make the displacing fluid possess viscosity to make the viscosity ratio, \( M \leq 1 \). It has to have the capacity to behave viscoelastic.

Considering these conditions, analysis of the rheological behavior of the fluids at low shear rate conditions is important in rheological considerations.

7. Conclusions

To properly evaluate the rheological behavior of drilling fluid, all the readings taken from the viscometer at low and high shear rates should be analyzed together. That would give a proper representation of fluid behavior. The rheological parameters determined would represent both flow behavior in the pipe and annulus. The ability of the fluid to perform the functions should be checked with the results. The parameters would be used to select the suitable rheological model and applied in the equations during hydraulics analysis.
To prevent pore blockage by the use of an EOR fluid, it is desirable to have a viscoelastic and shear thinning fluid. These fluids must have the ability to accelerate and decelerate when passing through narrow pore channels to maintain a constant volumetric flow rate. Stretching and extensional forces are generated along the flow axes. Also, contact of fluids with pore walls generates shear forces. For cost efficiency, the prevention of polymer loss is desirable by the creation of a stable fluid front. This is achieved by a mobility ratio less than one that would prevent viscous fingering. Rheology test results from viscometer readings taken at low shear rates might be preferable for tests on EOR fluids. Type 1 viscometers might be considered most relevant for the purpose. In other words, low shear rate viscosity should be monitored. This is because too high viscosity at low shear rates for injection into the reservoir away from the wellbore might cause an undesirable pump pressure increase. Also, since the desire is to maintain a stable fluid front as well as excellent flow behavior, the application of fluids that exhibit shear thinning and shear thickening behavior is preferable. Synthetic polymers tend to exhibit such qualities and might be preferable to biopolymers that are merely shear thinning.

Nomenclature/abbreviation

BP  Bingham plastic
EA  absolute error
EAA absolute average error
EOR enhanced oil recovery
ER  electrorheological
HB  Herschel Bulkley
HPAM hydrolyzed polyacrylamides
M  mobility ratio
MR  magnetorheological
NPs nanoparticles
PL  Power Law
YP  yield point
k  consistency factor
n  flow behavior index
τ  shear stress
γ  shear rate

Key concepts

Historically, drilling optimization aims to maximize the rate of penetration as an objective function. This is achieved by selecting optimum values of the mechanical parameters and hydraulic factors such as weight-on-bit, rotary speed, flow rate, and nozzle size for drilling bits furnished with nozzles. These variables are affected by uncertainties such as variations in formation lithology, the drill-string configuration, borehole quality, drilling fluid, etc. However, both drill bit hydraulics and drilling mud hydraulics are rig circulating system considerations influenced by pseudoplastic behavior. Similarly, during the life of a well, operating companies desire to maximize production. Nonetheless, some factors tend to retard the process of achieving this goal. An enhanced oil recovery mechanism has been in use to maximize recovery by alteration of the properties that hinder production for improved recovery.
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