With global oil and gas demand driving additional exploration in deeper plays, operators increasingly rely on accurate measurement of flow and thermal stability in oil-based drilling fluids in extremely high pressures and temperatures. Fluid loss from thermal instability and associated complications can hobble even the best designed drilling programmes.

In challenging high pressure, high temperature (HPHT) environments, operators continue to prefer invert drilling fluids to water-base systems because of the former’s superior thermal stability. But little rheological data from extreme HPHT conditions above 500 °F and 30 000 psi have been published due to a lack of suitable drilling fluid and viscometers.

However, recent tests by M-I SWACO and Texas A&M University, using four types of HPHT viscometers, have led to a simple rheological model to predict oil-base mud (OBM) behaviour under extreme HPHT conditions.

As conventional reserves dwindle, the development of HPHT wells (typically defined as wells with initial temperatures greater than 300 °F and pressures above 10 000 psi) has intensified in ultra deepwater and onshore unconventional plays.

Approximately 87% of global players are involved in HPHT wells in some capacity, with most indicating the start of HPHT programmes in the coming years in the USA, North Sea, Middle East, Southeast Asia and elsewhere.

Understanding drilling fluid rheological properties is imperative to reduce the risk of drilling failure, especially in extreme HPHT horizons greater than 500 °F and 20 000 psi in which drilling fluid chemicals undergo thermal degradation.

Typical HPHT viscometers are capable of test conditions of 500 °F and 20 000 psi, but newly introduced viscometers can reach test conditions of 600 °F and 30 000 psi. One new viscometer can withstand 40 000 psi, helping operators monitor fluid conditions in the harshest of downhole environments.

The tests compared rheological properties of invert drilling fluid using the Chandler 7600, Chandler 7500, Grace M7500 and Fann 75 models. The Chandler 7600 was used to generate rheological data under extreme conditions for modelling work.

A simple sequence was used to compare rheological data from the viscometers (Table 1). Six-speed sweep readings were taken with the fluid at various temperatures and pressures followed by 10 sec. and 10 min. gel-strength measurements before moving to the next step.

Using the Fann 35A, the first data point was collected at 150 °F without pressure to check instrument calibration and fluid properties. The 600 and 300 rpm readings of low-toxicity mineral oil used in testing were measured from ambient to 300 °F and 35 000 psi using the Chandler 7600. Figure 2 shows the 600 rpm readings as a function of pressure for different temperatures.

The viscosity of the mineral oil increased exponentially as the pressure increased at ambient and higher temperatures as expected, with 600 rpm readings dropping rapidly in higher temperatures as the mineral thinned.
Extreme HPHT test of conventional invert drilling fluid

Although most invert drilling fluids can be easily formulated for normal HPHT applications up to 400 °F, the same invert drilling fluid may become unstable above it.

To understand behaviour of conventional oil-base fluid under those conditions, two conventional fluids were tested using the Chandler 7600 viscometer.

After four hours exposure, the conventional fluid showed expected 600 rpm readings less than 100 up to 400 °F and 20 000 psi. But above 500 °F at 20 000 psi, the fluid showed erratic 100 rpm readings. At 500 °F/30 000 psi, failed viscous fluid had separated into a thick paste at the bottom of a dissembled cell and a clear oil phase on top. A second test showed similar results, although failure was less apparent from the dial reading plot.

If the HPHT viscometer could not reach the extreme HPHT conditions to induce failure, the invert drilling fluid could mistakenly be considered thermally stable, especially if extreme HPHT properties are extrapolated from data obtained at lower temperatures and pressures.

To ensure that the testing fluid would not fail, the thermal stability was evaluated by heat ageing at different temperatures up to 525 °F and then determining fluid properties. Extreme HPHT invert fluid, designed for conditions up to 600 °F, showed stable properties after heat ageing, suggesting good thermal stability for testing. There was no fluid failure when it was tested to the maximum capacity of the extreme HPHT viscometer at 600 °F and 40 000 psi.

Heat stress history

Heat stress history can affect an invert drilling fluid under extreme HPHT conditions, especially when the test fluid has been previously stressed under HPHT conditions. A quick comparison was conducted to investigate the effect of using an unheat-aged and a 400 °F heat-aged HPHT invert drilling fluid.

Figure 3 shows the rheology profiles of these two fluids at 400 °F/20 000 psi and 600 °F/40 000 psi conditions. The 400 °F heat-aged fluid (dashed lines) always shows a lower rheology profile, particularly at low shear rates compared to the unheat-aged fluid (solid line).

The difference was less significant at 400 °F/20 000 psi, but more significant at 600 °F/40 000 psi. The difference is thought to stem from thermal modification of the system.

Extreme HPHT invert drilling fluid was tested on the four HPHT viscometers to compare the 6-speed readings.

Data indicated that all the instruments can generate 6-speed readings reasonably close to each other in the absence of pressure. But under HPHT conditions, the results varied. The differences became more significant at higher temperatures and pressures, likely a reflection of different instrument designs.
Since most of these instruments rely on an ideal ‘frictionless’ pivot and jewel design for readings, the ideal condition may not be achieved if the test can be affected by temperature, pressure, solids content, type of solids and time of usage.

**Extreme HPHT measurements and simulation**

A 19 lb/gal. extreme HPHT invert drilling fluid was repeatedly tested on the Chandler 7600 using a matrix to get as many data points as possible (see Figure 4). The 6-speed readings and gel-strength measurements were made at each desired temperature and pressure combination.

Once rheological data were collected, the results were analysed and plotted against pressure and temperature. Curve fitting based on exponential function was then applied to obtain constant A & B in the form of \( \mu = A \exp(B \cdot P) \) where \( \mu \) is dial reading and \( P \) is pressure.

A similar approach could be used to evaluate the constant in the form of \( \mu = A \exp(B/T) \), where \( T \) is temperature, although curve fitting for temperature dependence correlation was not as good as pressure dependence correlation.

An alternative approach was used to determine temperature dependence because both constants are only pressure dependent. The two constants of each equation at different pressures were plotted against temperature and an exponential function was fitted over the curves. The exponential equations used were

\[
A = a \exp(-b \cdot T) \quad \text{and} \quad B = c \exp(-d \cdot T),
\]

where constants \( a, b, c \) and \( d \) were graphically determined.

As a result, the original pressure-dependent exponential equation can be used to correlate viscosity with pressure and temperature, in which both \( A \) and \( B \) are temperature dependent. The equation is used to simulate rheology of invert drilling fluid under different temperature and pressure conditions.

The simulation appeared to be reasonably close for runs at 150 °F, 220 °F, 450 °F and 550 °F, but was considerably off for the mid-temperature ranges, partly from data quality and temperature correction constants.

But the simulation showed that the behaviour of invert drilling fluid can be simulated, if the thermal stability of the invert drilling fluid can be proven.

The simulation also can be used to estimate rheological properties that cannot be directly measured under certain conditions using any HPHT viscometers, such as low temperature, high pressure or low pressure, high temperature.

Using and evaluating HPHT viscometers, engineers identified concerns for extreme HPHT projects:

1. **Jewel and pivot design**

   Fast wearing of pivot and fracturing of the jewel can take place easily and quickly at 600 °F and 40 000 psi from long running time, high speed of rotation, and high solids content. However, improvements by one manufacturer can improve the life span of the design.

2. **Temperature and pressure controls**

   Temperature control becomes a tricky task under prolonged HPHT testing because of the location of temperature sensors, the volume of test fluid and the massive amount of metal in the test cells. Overheating and under heating has been observed when the temperature was supposed to be held constant while testing at two different pressures. The temperature can continue to rise while waiting for the 10 min. gel.

3. **Automatic mode vs. manual mode**

   Dangerous situations can result in HPHT in automatic mode for data collection, if temperature and pressure regulating components malfunction. Those risks increase in extreme HPHT conditions. The instrument should be pressurised to maximum capacity at room temperature to ensure proper sealing of the whole system before testing to avoid sudden pressure losses.

4. **Maintenance and calibration**

   The temperature and pressure gauges on the HPHT viscometers should be calibrated regularly and in-line filters cleaned or replaced to extend the life of pressure regulators and avoid hazardous situations.

5. **Mixing of confining fluid and test sample**

   In tests, the exact capacity of the cell was measured and the fluid level controlled within ±5 ml to avoid mixing and unexpected drops in rheology at extreme HPHT conditions from the influx of confining fluid under extreme pressure.

6. **Fluid composition and thermal stability**

   Proper fluid composition and product chemistry are essential to ensure thermal stability under extreme HPHT conditions. Without proper thermal stability, simulations using properties obtained at lower temperature and pressure are unreliable.

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**Table 1. Temperature/pressure schedule used for HPHT rheology measurement of invert drilling fluid**

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>Pressure (psi)</th>
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</tr>
<tr>
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<td>5000</td>
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<td>30 000</td>
</tr>
<tr>
<td>600</td>
<td>40 000</td>
</tr>
</tbody>
</table>

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**Figure 4. An ideal test matrix for extreme HPHT data collection.**