



Gap Analysis Assessment of Performance of Conventional Drilling Fluids in High Temperature and High Pressure Environments

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ABSTRACT: The critical functions performed by drilling fluids during drilling operations include providing hydrostatic pressure to prevent formation fluids from entering into the wellbore, keeping the drill bit cool and clean during drilling, carrying out drill cuttings, and suspending the drill cuttings while drilling is paused. Others include control of formation pressures, prevent well-control issues, maintaining wellbore stability, minimize formation damage, cuttings transport from the wellbore to surface and minimize risk to personnel, the environment and drilling equipment. In adverse drilling environments such as High Pressure High and Temperature (HPHT) wells, the elevated temperatures and pressures encountered by the drilling fluids downhole may limit their technical performance and result in drilling problems if these factors are not well considered during the drilling fluid design. Hence, the objective of this study is to carry out a gap analysis on the performance of conventional drilling fluids in high pressure and high temperature environments using appropriate engineering methods. The outcome of the study identified some of the limitations of drilling fluids in HPHT drilling environment such as loss of rheology property control, fluid gelation at high temperature, high fluid loss at HPHT conditions, thermal degradation of the drilling fluid constituents, sagging of weighting materials etc. Benchmarks such as thermal stability of drilling fluid products and system, resilience to high temperature gelation, resistance to high temperature fluid loss, stable rheological properties control, resistance to solids sagging in HPHT environment etc were identified as top criteria for optimal performance of drilling fluids systems in HPHT wells. Potential steps or actions that that may be taken to bridge the existing gaps or shortcomings of conventional drilling fluids in HPHT drilling environment were then recommended.

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Drilling fluids perform certain critical functions during drilling operations such as control of formation pressures and well control, maintaining wellbore stability, cuttings transport from the wellbore, etc. In adverse drilling environments such as High Pressure High Temperature (HPHT) wells, the elevated temperatures and pressures encountered by the drilling fluids downhole may limit their technical performance and result in drilling problems if these factors are not well considered during the drilling fluid design. Wells with a high bottom hole temperature and pressure in the excess of 300°F and 10,000Psi respectively are

considered as high pressure, high temperature HPHT wells (Oriji, 2015). Due to the challenges posed by HPHT environment to the drilling process, the high wellbore temperature causes thermal degradation of drilling fluid additives, agents or constituents of the drilling fluid system (Rommetveit and Bjorkevoll, 1997). One of the key characteristics of HPHT wells is the existence of small margin between pore pressure and fracture pressure as well as elevated bottom hole temperature. This characteristics of HPHT wells present a series of challenges to both drilling fluid management at bottom hole condition and well control

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incidents. Literature survey puts well control incident rate for conventional wells at 4 to 5% whereas in non-conventional wells such as the HPHT wells, an alarming rate of 100 to 200% or even greater has been recorded. This represents at least one well control incident in every 20 to 25 wells drilled for conventional wells and at least one to two well control incidents for every non-conventional well like HPHT wells (Auwalu *et al.*, 2015). Very high bottom hole temperature and pressure actually degrades the rheological properties of conventional drilling fluids causing both dynamic and static barite sag thereby increasing the risk of loss of well control more particularly in high angle wells. HPHT wells are considered critical because of the more severe well conditions like borehole instability, fractured formation and excessive lost circulation, thus several design processes are needed to be considered to ensure that HPHT wells are drilled safely and economically to the desired depth (Oriji *et al.*, 2012). Uncontrolled changes downhole in the drilling fluid's pressure and temperature will modify the rheological properties of drilling fluid which may adversely impact on the fluid's ability to carry out vital drilling functions (which are related to the fluid's properties) such as hole cleaning, cuttings removal, wellbore hydraulics, balancing formation pore pressure, etc. Due to high bottom hole pressure in HPHT wells, high density drilling fluids are required for drilling HPHT wells. This could result in high solids loading which might lead to barite sagging and high frictional pressure losses in the annulus of the wellbore. With the bottom hole temperatures higher than 205 °C (400 °F) in the well, the drilling fluid, regardless of the base (water, oil or synthetic oil), get a bit more than 40% solids in its composition. Thus to remain stable and functional, the drilling fluid requires constant dynamic conditions downhole. This is because the high temperature present in the drilled area affects and changes the rheological properties to a point of null effectiveness leading to hole instability problems and influences of abnormal pressure zones. When the temperature reaches 210 °C (with pressure ranges from 15,000 psi to 18,000 psi) the drilling fluid properties begin to decrease, indicating that is the point where the additives lose performance and efficiency (Ruiz, 2016). For the purpose of this study, efforts were made to first ascertain the current or actual performances of conventional drilling fluids in HPHT drilling environments. Next, the benchmarks or desirable optimal performance indicators of drilling fluids in HPHT wells were identified. These standards will be used as the references for adjudging the success of the drilling fluids performances in HPHT drilling environments. i.e. what is most important or critical? Subsequently, the gaps between actual performances

of conventional drilling fluids in HPHT drilling environments and their desirable optimal performances will be analyzed to get to the root of the problem. The limitations encountered by conventional drilling fluids in HPHT drilling environments were evaluated. Potential steps or research opportunities that may bridge the existing gaps or shortcomings with drilling fluids in HPHT drilling environment were distinguished. What are the limitations of these conventional drilling fluids in HPHT environments? What critical factors limit their performance in HPHT environments? Are there some novel/innovative substitutes that give us the opportunities to close these gaps? Can we attempt newer additives, products or novel combination of some of these important drilling fluids' additives, agents or products in such a way that ultimately improves their performance in HPHT drilling environments over the actual performance of conventional drilling fluids?

Actual Performances of Conventional Drilling Fluids in High Pressure High Temperature (HPHT) Wells:

The actual technical performances of conventional drilling fluids in HPHT wells are impaired by the harsh operating environments of temperature and pressure in which the drilling fluids are subjected to during drilling operations. The challenges faced by drilling fluids in HPHT drilling environments have been well documented in several literatures and are summarized below;

High Temperature Gelation: In water based drilling fluids (WBDFs), flocculation (colloidal particles come out of suspension to sediment under the form of floc or flake) of clay or bentonite is worsened by the thermal deterioration of thinners, PH drop, and an increase in filtrate loss. Flocculation of colloidal particles like clays, fluid-loss additives and breakdown of emulsifiers may also raise gelation in oil based drilling fluids (OBDFs). Logging the pressure required for gel breaking is imperative to halt the surge pressure in HPHT wells, where if drilling fluid circulation is resumed quickly it might lead to loss circulation (Radwan *et al.*, 2011).

High Temperature Fluid Loss: The combination of high temperature, gelation effect and degradation of synthetic polymers due to thermal effects, will induce static and dynamic fluid losses in the drilling fluid. These losses need to be kept as low as possible to minimize filtrate invasion and reduce formation damage (Davoodi *et al.*, 2018).

Loss of Rheology property control: Thermal instability will induce changes in the fluid rheology which may

adversely impact the drilling efficiency. Unsuitable rheology of drilling fluid can cause problems, such as inappropriate pressure losses and dispersion of clay. Furthermore, excessive surge pressure and swab can occur with little increases in colloidal-size drilled solids. These solids improve the rheological properties of the fluid (Kakadjian *et al.*, 2019). Levels below the acceptable values of rheological properties can cause other problems such as inadequate hole cleaning, segregation of weighting material, and an inconsistent fluid density profile in the annulus which may lead to loss of drilling fluids or well control problems (Ali *et al.*, 2020).

Thermal degradation of drilling fluid constituents: Most drilling fluid products are susceptible to thermal degradation at high temperature. The drilling fluid properties may deteriorate under HPHT static conditions causing variation in the drilling fluid density downhole and causing fluid loss and its attendant's consequences (Zhong *et al.*, 2019).

Barite (weighting agent) Sagging: The solids-carrying function of conventional drilling fluid may deteriorate under HPHT conditions, prompting dynamic and static barite sagging. (Sagging: weighting materials separate from the liquid phase and settle down). The barite sag can result in big variations in the mud density in the wellbore with the light density at the top and heavier density at the bottom. The ability of a mud to suspend barite under dynamic conditions certainly is important; however, other factors may be equally significant. The sag index is the product of the mud weight difference measured in the viscometer and four constants based on key operational factors affecting sag: well bore inclination, flow regime, hole diameter, and length of the inclined well bore. In vertical wells, barite sagging occurs when circulation is stopped whereas in deviated wells, the complex trajectory results in complex settling mechanism (boycott settling) which can cause quick settling even during circulation. Heavier particles settle at the low side of the wellbore while lighter fluids settle at the high side. Sagging of weighting agents occurs most often in low viscosity or low gel strength fluids, low shear rate conditions, freshly prepared drilling fluids with minimal solids and in high temperature wells due to the reduced downhole fluid viscosity of the drilling fluid as a consequence of the increased downhole temperature (Petrowiki, 2016, Basfar *et al.*, 2018). If not well managed, fluctuations in the mud density in the wellbore could lead to well control issues, differential pipe sticking, lost circulation, poor drilling fluid hydraulics symptoms, inadequate hole cleaning, cuttings bed accumulation risks and induced wellbore instability problems

High or Uncontrollable ECD in narrow drilling windows: Downs *et al.* (2011) detected that high loading of barite in typical drilling fluids increased frictional pressure losses when circulating in long sections, leading to unacceptably high ECD in narrow operating drilling windows which could lead to fracturing the well, fluid loss and thus increasing the risk of losing well control in the case of high angle wells.

Gas solubility in drilling fluids (especially in Oil Based Drilling Fluid): Conventional oil-based drilling fluids usually takes up large volumes of gas influx during drilling due to the solubility of the gas influx in the base oil. Drilling fluids kept static for long periods in long horizontal sections create well control problems and deteriorate drilling fluid properties. Even when water based drilling fluids (WBDFs) are used, the diffusion effect still exists, although to a much smaller extent (Bradley *et al.*, 2002). The gas influx dissolves in the oil phase of oil based drilling fluid and produces a new fluid mixture with unique phase equilibrium. This new mixture is in the liquid phase and has its own distinctive bubble point pressure, this makes the detection kick harder (Aberdeen Drilling School and Well Control Training Center, 2008). This new mixture (gas dissolved in the drilling fluid) will destabilize the formulation, and impair the carrying capacity of drilling fluid, raising weighting material (barite sag), precipitating cuttings, and affect viscosity agents, in particular, clays (Bradley *et al.*, 2002).

High Density Drilling fluid Requirement in Narrow Drilling Window: High density requirement for drilling fluids to counteract anticipated formation pore pressure dictates that the drilling fluids are weighted up with high density solids such as barite which are commonly known to exhibit sagging under both static and dynamic well conditions. This problem (sagging or segregation of the weighting materials) arises from challenges occurring downhole in the well such as lost circulation, rising torque and drag, ECD fluctuations, inclined or horizontal well geometry, operations or activities that requires drilling fluids to be static for long periods etc. The narrow drilling window dictates that there is a narrow margin for error for ECD fluctuations which if not well managed, may lead to kick intake, formation fracture, lost circulation, loss of well control etc. Liu *et al.* (2019) remarked that drilling fluid specialists and engineers are required to provide solutions to these challenges by finding adequate fluid formulations of good continuous performance in all adverse condition. The fluid must have an excellent thermal stability with extreme pressure consistency so that it poses little or no alteration to the formation to

ensure hole integrity and wellbore stability, contain formation pressure with minimum invasion, achieve a satisfactory rate of penetration (ROP), suspend the weighting material under a variety of conditions etc thereby improving the drilling efficiency of the operations (Liu *et al.*, 2019., Shah *et al.*, 2012., Apaleke *et al.*, 2012). Therefore, the choice of drilling fluids for HPHT operating environments demands thoughtfulness and consideration of several critical factors, such as the anticipated formation geology, formation pore pressure and fracture gradient, downhole pressure and temperature environment, required fluid hydraulics, desired optimal rheological properties of the drilling fluids etc.

Benchmarks for Design of Drilling Fluids for HPHT Conditions: We will consider the yardsticks or indices which are vital for optimal technical performance of drilling fluids in HPHT drilling environment i.e the desirable optimal performance criteria for HPHT drilling fluids. HPHT well drilling process is quite challenging and require a robust drilling fluid program (formulation) in order to meet the design intention. Bern *et al.* (2006) and Gao *et al* (2002) had earlier remarked that the important criteria in selecting base drilling fluid for HPHT operations as being the environmental impacts, the fluid stability at high pressure and temperature and the minimum rheology required to minimize ECD and reduce the frictional pressure loss. Ali (2020) also mentioned a number of considerations to note as indices for selecting drilling fluids for HPHT drilling. After careful root-cause analysis, the following criteria or points-to-ponder have been identified as top priorities for selection of drilling fluids systems for HPHT drilling environment.

High Density, Low Viscous Requirements of Drilling Fluids: The significance of balancing the need for thin or low viscous, low incremental pressure drilling fluid without creating problem of poor solids support (sagging or settling of weighting materials from the fluid). The narrow drilling window in such wells implies that there is a narrow margin for error for ECD fluctuations resulting from barite sagging or other factors which could lead to uncontrollable ECD. In addition, the high density drilling fluids particles may plug the nano-pores in unconventional reservoirs, especially in shale reservoirs.

Thermal Stability of the Drilling Fluid Products and System: Destabilization of products, and aggressive and rapid reactions towards any contaminants in the system will occur when the products in the drilling fluid system reach their operating condition limits. The products or constituents of the drilling fluid system must be able to endure HPHT conditions

without being degraded materially nor losing significant qualities of attributes (properties) that are fundamental to the functions they perform. The fluid and additives should not only be stable at high temperature but must also withstand the maximum expected time under the most extreme conditions anticipated.

Resilience to High Temperature Gelation: Colloidal particles such as clay particles and fluid-loss additives in the drilling fluids must be able to resist excessive flocculation or aggregation under high temperature which could lead to gelation. The emulsions in the drilling fluids system must also be able to endure high temperature without breakdown which may increase gelation in the drilling fluid especially in oil based drilling fluids.

Good Resistance to High Temperature Fluid Loss: The drilling fluids should be able to form an efficient filter cake even under static and dynamic HPHT conditions which will minimize filtrate invasion into the formation and reduce possible formation damage.

Robust Rheological Properties Control: This is one of the most important or overriding attributes that drilling fluids should possess. The drilling fluid must be able to maintain good rheological properties downhole in the HPHT conditions in the wellbore such as consistent fluid density in the annulus, plastic viscosity and yield point within the acceptable or desirable ranges, etc. These properties of drilling fluids are very critical for well control, adequate cuttings removal and hole cleaning and good rate of penetration. This would lead to an improvement in the drilling efficiency.

High Resistance to Solids Sagging in HPHT Environment: Drilling fluids meant for HPHT drilling must be able to include among other requirements, excellent properties for solids-carrying functions under HPHT conditions without easily prompting dynamic and static barite sagging (or segregation of weighting solids inside the drilling fluid system) during the drilling process. This would help to prevent excessive ECD build-up and manage the ECD fluctuations during the drilling process.

Gas solubility in drilling fluids (especially in Oil Based Drilling Fluid): Drilling fluids design for HPHT drilling must be able to prevent gas influx from easily dissolving in the oil phase of drilling fluids system to prevent it from producing a new fluid mixture with unique phase equilibrium (in liquid phase) and its distinctive bubble point pressure which would have made gas influx detection kick harder and

induce further problems such as destabilization of the formulation, impairment of the carrying capacity of drilling fluid, raising weighting material (barite sag), precipitating cuttings, and affecting viscosity agents, in particular, clays (Aberdeen Drilling School and Well Control Training Center, 2008., *Bradley et al.*, 2002).

Gap Analysis or Research Opportunities for HPHT Drilling Fluids: Most water based drilling fluids (WBDFs) possesses several problems related to drag and torque, pipe sticking, formation damage, lost circulation, and wellbore instability within HPHT downhole environments. High temperatures render the superior and thixotropic properties of polymers inactive, adversely affecting rheological characteristics and resulting in a loss of drilling fluid, inappropriate cutting, lifting barite sag problems and increasing the cost of drilling. Drilling engineers currently require thermally stable, multifunctional, environmental, and inexpensive durable drilling fluid additives for the drilling of unconventional HPHT reservoirs (Aftab, 2016). Oil-based drilling fluids (OBDFs) have been repeatedly used in HPHT drilling

fluid systems, where they have been shown to be effective in shale drilling in HPHT downhole environments. Oil-based drilling fluid is normally chosen for HPHT drilling as a means of tackling high temperature conditions because it is stable to at least 450 °F in 16-hr laboratory tests (Adamson, 1998). It typically exhibits a lower coefficient of friction, and it provides a thinner and more lubricious filter cake (Marinescu, 2014) . However, oil based drilling fluids have some drawbacks which include: high cost, influence on logging interpretation, absorb a large amount of gas (gas solubility), environmental issues, and the thermal expansion of oil-based drilling fluids is higher than in water based drilling fluids, which may lead to pressurization of the annulus (Downs, 2011 and Marinescu, 2014). Synthetic based drilling fluids (SBDFs) for HPHT drilling is another option to replace water-based drilling fluids since it is biodegradable and has low toxicity (compared with oil-based drilling fluids), i.e., environment acceptance of any waste generated including drilling cuttings. It exhibits thermal stability of up to 475 K (Smithson, 2016), and eliminates gas solubility effects.

Table 1: Current gaps (research opportunities) for HPHT drilling fluids (Ali, 2020, Proehl, 2006, Shadravan and Amani, 2012).

S/N	Desirable Optimal Performance of Drilling Fluids at HPHT Conditions (Benchmarks)	Actual Performance of Most Conventional Drilling Fluids at HPHT Conditions	Current Gaps (Opportunities) for Drilling Fluids for HPHT Drilling
1	Plastic Viscosity as low as reasonably possible (ALARP) to minimize ECD	high density, medium to high viscous drilling fluids	High density, low viscous drilling fluids with low ECD fluctuation tendency
2	Yield Stress and Gel Strength: Sufficient to prevent sag, but not so high as cause gelation, or high surge and swab pressures	Poor/moderate resistance to weighting agents sagging at HPHT environment, low/moderate resistance to high temperature gelation	High resistance to weighting agents sagging and fluid gelation at HPHT conditions.
3	HPHT Fluid Loss: As low as reasonably possible to prevent excessive fluid (continuous phase) loss, formation damage and risk of differential sticking	Moderate resistance to fluid loss at HPHT condition, thick filter cake	High resistance to fluid loss at HPHT condition, thin filter cake
4	HPHT Rheology: Stable and predictable to control sag, gelation and manage ECD	Poor rheological properties control in HPHT environment	Robust or stable rheological properties control in HPHT environment
5	Compressibility: Must be known to estimate downhole pressures and ECD	Unknown in some cases	Ability to estimate ECD at desired depth during Pre-drill design phase
6	Stability to Contaminants: Stable in presence of gas, brine and cement	Moderate stability to contaminants	High stability to contaminants
7	Poor gas solubility needed for accurate kick detection and modelling	High solubility of gas in drilling fluids (especially in oil based drilling fluid)	Low gas solubility in drilling fluids (especially in oil based drilling fluid)
8	Very good shale inhibition potential	Moderate to high shale inhibition potential	High shale inhibition potential
9	Stability to Aging Properties: do not change over time under either static and dynamic conditions but in reality properties may vary slightly	Poor to average stability of fluid properties to aging conditions	Excellent thermally stability of drilling fluid products and systems to aging conditions
10	Solid Tolerance: Properties insensitive to drilling solids	Poor to moderate solid tolerance to drilling solids	High solid tolerance to drilling solids
11	Weighting: short time requirement to weight up in the event of a kick	Longer time requirement to weight up in the event of a kick	Short time requirement to weight up mud time in event of a kick

The overall performance of synthetic based drilling fluid (SBDF) depends on the selection of the right combination of drilling fluid additives; for example,

the selection of an emulsifier to give an overall emulsion stability (Marinescu, 2014). However, conventional synthetic based drilling fluids still have

their own share of challenges in HPHT wells which includes barite sagging (leading to poorer ECD management) especially in deviated or horizontal wells, high temperature gelation, high temperature filtration fluid loss and poor rheology property control. Hence there is a need to conduct researches for innovative or novel, synthetic based drilling fluids for HPHT wells with high technical performance, environmental friendliness and cost effectiveness with a view to addressing the already existing challenges associated with conventional drilling fluids in HPHT drilling environment.

Conclusion: In this section, some action steps and recommendations have been provided to close existing gaps, which include the use of high density, low viscous drilling fluids with low ECD fluctuation tendency, weighting agents with high resistance to sagging tendency at HPHT conditions, drilling fluids with high resistance to high temperature fluid loss, drilling fluids with robust or stable rheological properties control at HPHT conditions, drilling fluids that indicate high stability or resistance characteristics to contaminants, drilling fluids with poor gas solubility properties, drilling fluids with excellent shale inhibition properties, fluids with excellent thermally stable drilling fluid products and system, drilling fluids with high solid tolerance to drilled solids, drilling fluids capable being weighted up rapidly if a kick is taken and drilling fluids with resilience to high temperature gelation

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