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RESEARCH ARTICLE-PETROLEUM ENGINEERING

An Overview of the Common Water-Based Formulations Used for Drilling Onshore Gas Wells in the Middle East

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Abstract
The proper selection of drilling fluids formulations and its treatment has always been a challenge and requires a great effort to ensure optimum drilling performance. The objective of this paper is to assist the mud engineer in selecting the water-based drilling fluid formulations that are best suited for a certain application. To achieve this target, the field practices were combined with the literature to study the most practiced water-based drilling fluid recipes used for onshore gas applications in the Middle East (i.e., spud mud, high-bentonite spud mud, salt/polymer mud, and high-overbalanced mud). From both field practices and deep literature review, it is recommended that both spud mud and high-bentonite spud mud be prepared and pre-hydrated for 4–6 h before a well spud. Also, it is important to add detergents with high-viscosity sweeps to avoid the bit balling and maintain the gel strength. While for salt/polymer mud, the regular addition of sodium sulfite is necessary for polymers stabilization, and the efficient solids control equipment performance is essential. To avoid the solids sagging issues associated with drilling high-pressure high-temperature deep gas reservoirs, it is recommended to either uses sag resistance materials, micronized weighting materials, or a combination of different weighting materials. The high-overbalanced mud is the most effective and efficient type when drilling a combination of natural fractured depleted gas reservoirs with high-pressure gas reservoirs.

Keywords Water-based · Drilling fluids · Onshore drilling · Gas wells · Middle East

Abbreviations

ALAP	As low as possible
bbl	Barrel
BHT	Bottom-hole temperature
gpm	Gallon per minute
HPHT	High pressure high temperature
HPWBM	High-performance water-based mud
LSYP	Low-shear yield point
MBT	Methylene blue test
PAC	Polyanionic cellulose
pcf	Pound per cubic feet
PHPA	Partially hydrolyzed polyacrylamide
PPT	Permeability plugging test
PSD	Particle size distribution
PV	Plastic viscosity
ROP	Rate of penetration
WBDF	Water-based drilling fluid
XC	Xanthan gum
YP	Yield point

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1 Introduction

Drilling fluids have a crucial continued role in drilling a successful well. They are designed to perform a variety of important functions at once. These functions are mainly controlling of subsurface pressures, carrying out and suspension of drill cuttings, maintaining of wellbore stability, minimizing formation damage, cooling and lubricating of the drill string and drill bit, sealing of permeable formations, transmitting hydraulic energy to downhole tools, and providing sufficient information for formation evaluation [1–3].

Generally, drilling fluids are composed of a continuous phase, either liquid or gas, mixed with active/inactive solids and chemicals. Based on the continuous phase, the drilling fluids are classified into three main types: (a) aqueous drilling fluids referred to as water-based mud, (b) nonaqueous drilling fluids also called oil-based mud, and (c) gaseous-based mud [2–5]. In the gaseous-based mud, gas or gas–liquid mixtures are used to be the continuous phase. This type of drilling fluid is not commonly used and applicable for drilling in depleted fields, where the depletion of the formation fluid generated a low formation pressure profile [1, 6]. In oil-based muds, the continuous phase is either synthetic oil or petroleum products, but the water can be added to form an invert emulsion. These drilling fluids are used much less frequently compared to water-based muds because of its high cost and the associated environmental concerns and legislations. However, they are beneficial in drilling horizontal wells and water-sensitive formations [4, 7–9].

The most common type of drilling fluids used in drilling operations is the water-based drilling fluid (WBDF). It consists of a mixture of solids, water, and chemicals, where solids might be active or inactive depending on its reaction with a water base and dissolved chemicals. The active solids (e.g., clays) react with water or dissolved chemicals to perform certain functions, unlike the inactive solids (e.g., sand) which do not react with water and chemicals to any significant degree. The used water might be seawater, brine, or freshwater, whichever is appropriate or available [2, 3, 10–12].

Many issues and problems associated with drilling operations are mainly affected by drilling fluids properties. These challenges, such as stuck pipe, wellbore instability, lost circulation, formation damage, and shale heaving, can be avoided eventually using a variety of additives types to maintain the key properties. The most common additives include densifiers, viscosifiers, rheology controllers, lost circulation controllers, filtration controllers, shale stabilizers, and alkalinity controllers [11, 13].

Considering the applied additives, i.e., rheological properties controllers and inhibition ions, the WBDF can be classified into four categories: (a) non-dispersed-non-inhibited mud system, in which neither rheology controllers nor inhibitors are contained, (b) dispersed-non-inhibited mud, that contains rheology controllers; however, the inhibitors were not utilized, (c) non-dispersed-inhibited mud contains inhibitors but not rheological properties controllers, and (d) dispersed-inhibited mud contains both rheological controllers and inhibition ions [2, 14–16].

The appropriate drilling fluids selection and design for drilling operations are governing by many key factors, such as formation type, pressure, temperature, well trajectory, economics, and environmental restrictions. To consider these factors, the collection of offset wells data, geological data, and others are necessitated. Generally, the proper selection of drilling fluids systems and its treatment has always been a challenge and requires a great effort to ensure optimum drilling performance [6, 11, 17, 18].

The objective of this paper is to assist the mud engineer in selecting the WBDF formulation that best suited for a certain application. To achieve this target, the field practices were combined with the literature to study the most practiced WBDF recipes in the middle east, which are used for onshore gas applications. These formulations were discussed from both theoretical and practical points of view, in terms of the composition, properties, drilled section/formation characteristics, potential problems, and recommendations, and supported by field cases.

2 Drilling Fluids Formulations

From the literature, the WBDF can be classified and described based on its composition as shown in Table 1. The common WBDF recipes used in the middle east, including spud mud, high-bentonite spud mud, salt/polymer mud, and high-overbalanced mud, will be discussed herein.

2.1 Spud Mud

The Spud mud is a formula of WBDF that is mainly categorized as non-dispersed-non-inhibited mud and used for drilling the shallow formations with large diameter hole (i.e., 36″–26″). It is composed of flocculated bentonite (mainly smectite/montmorillonite mineral) that is qualified for providing and maintaining the required viscous properties. This mud with its simple compositions will demonstrate the desired rheological properties for carrying out the large gravel cuttings from the shallow depth. However, weighting material might be used to maintain hole stability. Loss of circulation is highly likely to occur while drilling the soft shallow formations, so the loss of circulation control materials often be used [19, 20].

2.1.1 Composition and Properties

The spud mud is formed mainly by bentonite and water, but other functional additives (i.e., pH controller, weighting material, thinner and fluid loss controller) are required to maintain the mud properties in a range of 64–67 pcf (pound per cubic feet) for density, 7–10 of API filtrate and as low as a possible value of plastic viscosity. The most practiced composition of spud mud is listed in Table 2 with the average properties.

Table 1 General description of water-based drilling fluids types. Adapted from Growcock and Harvey [2]

Mud type	Main components	General characteristics
Freshwater	Freshwater	Cheap, onshore applications, space required to settle solids, high ROP at stable formations, flocculants may be required
Seawater	Seawater	Cheap, offshore applications
Spud mud	Bentonite, water	Cheap, surface hole drilling
Saltwater	Seawater, brine or saturated saltwater, saltwater clay, starch, cellulosic polymer	Reasonable cost, drilling salt and workovers
Lime or gypsum	Fresh or brackish water, bentonite, lime or gypsum, lignosulphonate	Reasonable cost, shale drilling, lenience with salt, anhydrite
Lignite or Lignosulphonate (Chrome or Chrome Free)	Fresh or brackish water, bentonite, caustic, lignite, or lignosulphonate	Reasonable cost, shale drilling, lenience with salt, high temperature, anhydrite
Potassium	Potassium chloride, acrylic, bio or cellulosic polymer, small amounts of bentonite	Reasonable cost, hole stability, high pH, low leniency with cuttings
Low solids ("non-dispersed" when weighted up)	Fresh or saltwater, polymer, small amounts of bentonite	Expensive, hole stability, low leniency with cuttings

Table 2 The composition of the spud mud and its average properties

Material	Unit	Quantity (per bbl.)	Function	Property	Unit	Value
Make-up water	bbl	As required	Based fluid	Density	pcf	64–67
Soda ash	lb/bbl	As required	pH adjustment	Funnel viscosity	sec/qt	60–120
Bentonite	lb/bbl	25–50	Viscosifier	pH	–	>10
Caustic soda	lb/bbl	0.20–0.35	pH adjustment	PV	cP	As low as possible (ALAP)
Thinner	lb/bbl	1 if required	to control viscosity when raising bentonite content to 35–50 lb/bbl	YP	lb/100 ft^2	25–35
Barite	lb/bbl	If required	Weighting material	10 s Gel	lb/100 ft^2	10–20
*Starch	lb/bbl	2–3	Fluid loss additive at low temperature	10 min Gel	lb/100 ft^2	25–75
*If needed to reduce the filtrate if losses encountered				API filtrate	ml/30 min	7–10

2.1.2 Drilled Section Characteristics

Considering a field case, two sections were drilled using the spud mud. These sections contain five formations as shown in the lithology column in Fig. 1(i). Formations A, B, and C were drilled with 34″-hole section while D, E, and F were drilled with 28″-hole section. Formation A is exposed at the surface and composed mainly of layers of sandstone, claystone, limestone, and marl with minor streaks of anhydrite and traces of chert. Formation B constitutes of dolomite and limestone with streaks of marl and claystone. Formation C contains anhydrite occasionally with very minor streaks of dolomite and limestone. Formation D is composed of dolomitic limestone with minor streaks of anhydrite and claystone especially toward the lower part. Formation E constitutes mainly of limestone interbedded with shale layers.

2.1.3 Operational Practices

The spud mud is prepared by pre-hydrating bentonite clay and diluting in the base water by 25–50 lb/bbl. To ensure the proper hydration of bentonite, the soda ash and caustic soda should be used for lowering the concentration of calcium and magnesium ions, respectively, in the make-up water to be less than 200 mg/l, that will adjust the pH to above 10, as well [21, 22]. The thinner and weighting material might be used to alter the properties if required.

The spud mud should be prepared for 4–6 h before using to warrant yielding the clay.

Since hole cleaning is affected by the solids control equipment, mud density, rheology, and cuttings characteristics; 80 mesh screens are utilized to handle a typical flow rate of 1000–1200 gpm (gallon per minute) and the de-sander and de-silter are used to discard the solids.

Practically, a loss of mud is allowed over the shakers to discard the maximum number of solids and maintain the low-

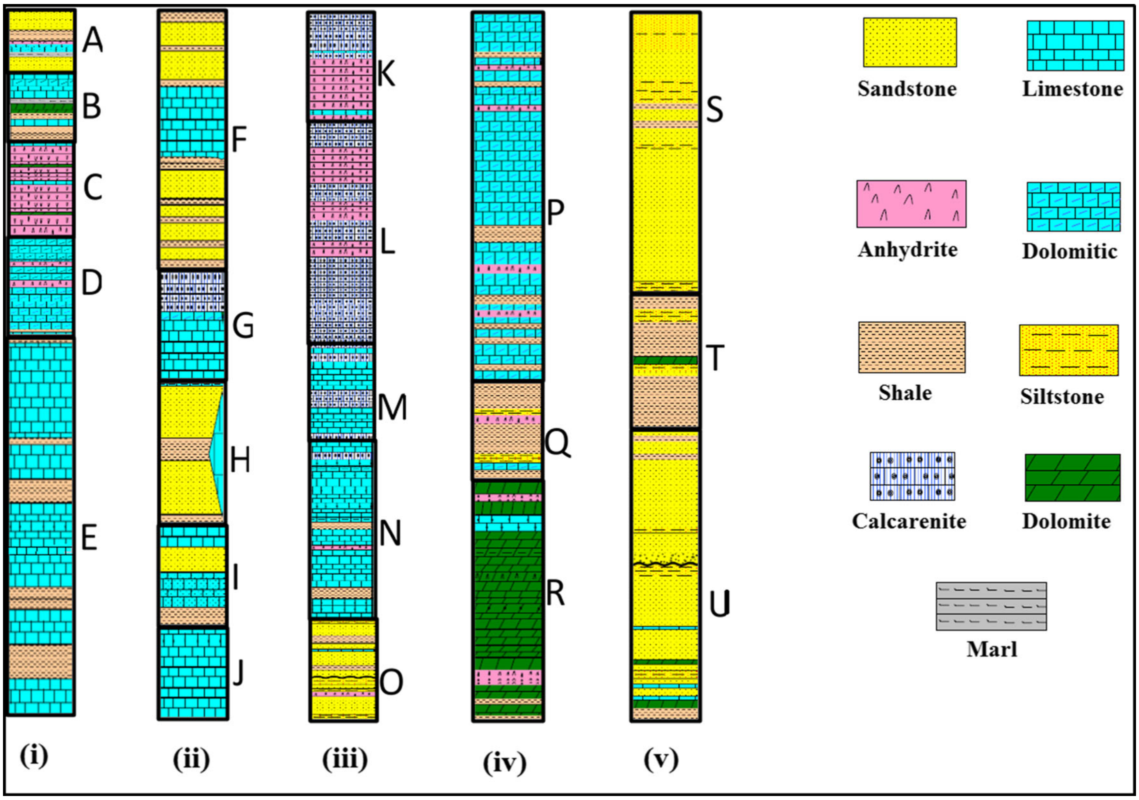

Fig. 1 Generalized lithology description of the drilled sections

est possible mud density in the active pits. Moreover, 100 bbl of high-viscosity sweeps is used every 30–45 ft together with reaming, and the swept volume is increased if there is a sign of hole instability or poor hole cleaning.

2.1.4 Problems and Recommendations

The bit balling problem will be experienced with the bentonite system if clay swelling is not inhibited. To reduce the occurrence of that, specific types of dispersant dubbed drilling detergent with high-viscosity pills are recommended to be used. This will help in carrying out the cuttings from the wellbore.

Based on the drilled section characteristics, a total fluid loss is the potential to occur. So, it is recommended to continue drilling 100–150 ft with mud, then switch to inhibited water and sweep hole with high-viscosity sweeps made from high-bentonite content.

In case of hole instability is a concern, inhibited partially hydrolyzed polyacrylamide (PHPA) mud and weighted high-viscosity sweep of 75 pcf are used to maintain the mud density at 63–64 pcf and pH at 9–10.

2.2 High-Bentonite Spud Mud

Surface hole formations have a low-pressure profile which promotes the possibility of circulation losses in specific geological horizons, besides the reduction in drilling rate of penetration caused by using bentonite [23]. Therefore, it had been recommended to use invert-emulsion mud. But, because of the environmental constraints, the invert-emulsion mud has a restriction when drilling the surface hole. As a result, and to help in averting losses of circulation; a high-bentonite spud mud has been introduced to drill such hole section.

2.2.1 Composition and Properties

The high-bentonite spud mud has the same components as the spud mud but with higher concentrations of flocculated bentonite and a thinner additive is required. An anti-microbial agent such as biocide may be required. The properties of this mud should be in a range of 67–69 pcf for density, 5–8 of API filtrate, and as low as a possible value of plastic viscosity. Table 3 shows the practically used composition for the high-bentonite spud mud and the averaging properties.

Table 3 The composition of the high-bentonite spud mud and its average properties

Material	Unit	Quantity (per bbl.)	Function	Property	Unit	Value
Make-up Water	bbl	As required	Based fluid	Density	pcf	67–69
Biocide	lb/bbl	0.25–0.35	Anti-bacterial	Funnel Viscosity	sec/qt	120–150
Soda ash	lb/bbl	As required	pH adjustment	pH	–	9–10
Bentonite	lb/bbl	40–50	Viscosifier	PV	cP	ALAP
Caustic Soda	lb/bbl	0.20–0.35	pH adjustment	YP	lb/100 ft^2	25–35
Thinner	lb/bbl	1–2	To control the viscosity	10 s Gel	lb/100 ft^2	12–20
Barite	lb/bbl	If required	Weighting material	10 min Gel	lb/100 ft^2	25–55
*Starch	lb/bbl	2–4	Fluid loss additive at low temperature	API Filtrate	ml/30 min	5–8
*If needed to reduce the filtrate if losses encountered				MBT	lb/bbl equiv.	40–50

2.2.2 Drilled Section Characteristics

The high-bentonite spud mud is used to drill a 22″-hole section which is composed of five formations as depicted in Fig. 1(ii). Formation F is composed mainly of sandstone interbedded with shale and limestone layers. Formation G constitutes of calcarenite, dolomitic limestone. Formation H contains mainly high compressive strength sandstone with minor streaks of shale and limestone. Formation I is composed of limestone with streaks of sandstone and shale. Formation J constitutes mainly of limestone.

2.2.3 Operational Practices

The high-bentonite spud mud is prepared similarly as the spud mud for 4–6 h before a well spud and pre-hydrated 40–50 lb/bbl of bentonite clay in the makeup water. Soda ash, caustic soda, and thinner will be used. The weighting material might be added to alter the properties if required.

The practical flow rate used to drill a section with the high-bentonite spud mud is 900–1000 gpm, which requires 60 mesh screens to be utilized. De-sanders and de-silters are used to discard as many solids as possible. For better hole cleaning, 75 bbl of high-viscosity sweeps is used every 30–45 ft.

2.2.4 Problems and Recommendations

Since the system contains a high concentration of bentonite, the bit balling problem is a concern. Therefore, detergents with high-viscosity pills are used.

From field practice, the optimum value of the methylene blue test (MBT) measurement, which indicates the active clay content in the mud, is 40–50 lb/bbl bentonite equivalent. But while drilling across formations that contain streak of shales (e.g., formations H and I), the MBT value will increase. So, a dilution rate of 20–25 bbl of water is used to maintain the MBT at the specific range.

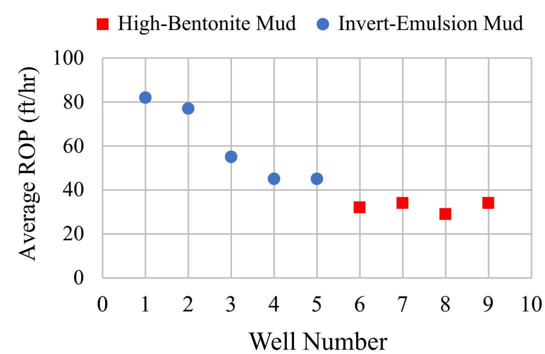

Fig. 2 Drilling ROP comparison between high-bentonite mud and invert-emulsion mud (field data)

When drilling into a formation containing a high compressive strength sandstone, such as formation H, the rate of penetration (ROP) is dropped significantly. The MBT, therefore, is recommended to be reduced to 25 Ib/bbl bentonite equivalent to enhance the drilling performance. Moreover, if a trip is made at casing point depth, it is recommended to add a powdered dispersant thinner to maintain the MBT and gel strength. That will minimize the effect of surge and swab pressures.

In case of total fluid losses encountered (e.g., taking place in formations F and G) or the borehole shows any instability or sticking tendency, it is recommended to switch to the PHPA mud system, and 75 pcf of mud cap to be pumped continuously into the annulus. This will maintain the maximum visible fluid level and prevent the water flow from formations (as occurred in formation F).

The drilling field data indicates that the ROP is reduced when using the high-bentonite mud comparing with invert-emulsion mud, as shown in Fig. 2. This reduction in the ROP is mainly due to the high-bentonite effect on the mud rheological properties [24]. Therefore, it is recommended to add thinner for the mud formula to control the mud viscosity.

2.3 Salt-Polymer Mud

Unstable shales and hard salt formations, that composed of sodium, magnesium, or potassium chlorides, are penetrated in many drilling areas. In which, using the oil-based mud has better performance and stability [25]. However, to be in line with the environmental regulations, an environmentally acceptable alternative WBDF (i.e., salt/polymer mud) has been developed to supersede the use of oil-based mud [26–29].

The salt/polymer mud is used to maintain shale stabilization and to avoid shale sloughing and hole enlargement caused by the dissolution of formation-salt [29]. Besides, it is used for high-pressure high-temperature (HPHT) conditions with a limitation of temperature up to 300 °F [30–33]. The key mud properties that need to be controlled are mainly mud salinity, density, rheology, filtration properties, and pH [29, 34].

2.3.1 Composition and Properties

The typical salt polymer mud contains mainly (a) base water, (b) pre-hydrated bentonite to viscosify the mud, (c) sodium or potassium salts (NaCl/KCl) for clay hydration inhibition, (d) a combination of anionic polymers such as xanthan gum (XC polymer) and polyanionic cellulose (PAC) for viscosity buildup and filtration control, (e) either caustic soda, caustic potash or soda ash to control the alkalinity, (f) starch for fluid loss control at low temperature, (g) barite as weighting material, (h) calcium carbonate ($CaCO_3$) as a bridging agent, (i) sodium asphalt sulfonate to improve filter cake properties, and (j) lignosulfonate to enhance the gel strength at high temperature [35, 36]. Tables 4 and 5 present the practical compositions for salt polymer mud used with normal and high densities for HPHT, respectively.

2.3.2 Drilled Section Characteristics

From the field case, the salt polymer mud is used to drill two sections. The first section has a 16″-hole and contains five formations (K–O) as described in the lithology column; Fig. 1(iii). Formations K and L are composed of layers of calcarenite and anhydrite with minor streaks of limestone. Formation M contains limestone and calcarenite. Formation N constitutes of limestone with minor streaks of calcarenite, claystone, and anhydrite. Formation O is composed mainly of sandstone interbedded by shale, siltstone, anhydrite, and limestone. The second section has a 12″-hole and contains three formations (P, Q, and R) as shown in Fig. 1(iv) and considered as HPHT formations. Formation P contains mainly of dolomitic with streaks of anhydrite and shale. Formation Q is composed mainly of shale with streaks of anhydrite, siltstone, and dolomitic. Formation R constitutes mainly of dolomite with interbeds of shale, limestone, and anhydrite.

2.3.3 Operational Practices

A low mud density of 67 pcf is used to start drilling the section to build up a filter cake, especially in some formations, such as formation K and the upper part of formation L, which have a potential risk of losses. Then, the mud density is raised to a certain level to overbalance the lower formation L pressure.

For this drilled section, when the static bottom-hole temperature (BHT) reaches 230 °F or If HPHT filtration control becomes problematic because of BHT, PAC low viscosity is introduced at 0.5–2 lb/bbl as required to control fluid loss especially at lower formations N and O. Small additions of sodium sulfite would remove the oxygen and stabilize the polymers to a bottom hole temperature up to 280 °F.

An efficient solids control equipment performance is essential to control mud density and viscosity, hence, minimize the probability of loss of circulation. 100 mesh screens are used to utilize the practical flow rate of 650 gpm.

It is possible to lose circulation when drilling into depleted formations. Therefore, it is highly recommended to conduct an API-HPHT filtration test before entering such formations.

A mud cap is pumped continuously in the annulus to maintain the maximum visible fluid level to prevent any flow from protentional formations. For a better hole cleaning, 75 bbl of a high-viscosity sweep is used every 45 ft.

When drilling through a section with HPHT formations (i.e., formations P, Q, and R), high mud density (up to 150 pcf) is required, and regular additions of sodium sulfite (1 can every 4–6 h) while drilling is necessary to stabilize the polymers to a bottom hole temperature up to 300 °F. 120–140 API mesh shaker screens are recommended for this hole section.

Any treatment should be pilot tested before adding to the active system, this is very crucial on this type of mud as any undesired addition can lead to excessive rheology or an increase in fluid loss properties. Once the final formulation is achieved, a visual sag settling test is performed at ambient temperature for 12 h.

2.3.4 Problems and Recommendations

CO_2 influx may take place in the mud, so frequent measurement of alkalinities is required. In the case of CO_2 influx occurrence, caustic soda and lime are effective in removing CO_2. If H_2S has been detected, the drilling fluid should be treated with chemical scavengers.

At HPHT conditions (i.e., formations P, Q, and R), where higher density mud is required to suppress the formation pressure [37], the settling rate of barite solid particles is increased [38]. This settlement is known as a sagging phenomenon and is affected by the drilling fluid properties and drilling param-

Table 4 The composition of conventional density salt polymer mud and its average properties

Material	Unit	Quantity (per bbl.)	Function	Property	Unit	Value
Make-up Water	bbl	As required	Based fluid	Density	pcf	As required
Bentonite	lb/bbl	5–15	Viscosifier	pH	–	9–10
XC Polymer	lb/bbl	0.5–1.25	Viscosifier	PV	cP	ALAP
Starch	lb/bbl	3–6	Fluid loss additive at low temperature	YP	lb/100 ft^2	24–34
PAC	lb/bbl	0.5–2	Fluid loss additive at high temperature	10 s Gel/10 min Gel	lb/100 ft^2	8/12
KCl/NaCl	lb/bbl	5–60	Shale inhibition	API Filtrate	ml/30 min	3–5
Caustic Soda	lb/bbl	0.25–0.75	pH adjustment	HPHT Filtrate at 250 °F and 500 psi	ml/30 min	< 16
$CaCO_3$ (Fine + Medium)	lb/bbl	5 + 5	Bridging material	HPHT Filtrate cake thickness	32nd in	1–2
Barite	lb/bbl	151	Weighting material	MBT	lb/bbl equiv.	7.5–10
Sodium Sulfite	lb/bbl	0.25–0.3	Oxygen scavenger	Solid content	vol%	< 5
Soltex	lb/bbl	2–4	Shale inhibition	Cl^-	mg/l	± 40 K

Table 5 The composition of 150 pcf density salt polymer mud for HPHT and its average properties

Material	Unit	Quantity (per bbl.)	Function	Property	Unit	Value
Make-up Water	bbl	As required	Based fluid	Density	pcf	150
Bentonite	lb/bbl	2.5	Viscosifier	pH	–	9–10
XC Polymer	lb/bbl	0.15	Viscosifier	PV	cP	ALAP
Soda Ash	lb/bbl	0.25–0.3	pH adjustment	YP	lb/100 ft^2	30
PAC	lb/bbl	6	Fluid loss additive at high temperature	10 s Gel/10 min Gel	lb/100 ft^2	12/24
KCl/NaCl	lb/bbl	5–60	Shale inhibition	API Filtrate	ml/30 min	< 6
Caustic soda	lb/bbl	0.5–1	pH adjustment	HPHT Filtrate at 300 °F & 500 psi	ml/30 min	< 18
Resinated Lignite	lb/bbl	6–10	Filtration control at HPHT	HPHT Filtrate cake thickness	32nd in	1–2
Barite	lb/bbl	642	Weighting material	MBT	lb/bbl equiv.	< 5
Sodium Sulfite	lb/bbl	0.25–0.3	Oxygen scavenger	Solid content	Vol %	< 5
Lignosulfonate	lb/bbl	2–4	Rheology control	Cl^-	mg/l	< 40 K
Soltex	lb/bbl	2–4	Shale inhibition			

eters [39–41]. This issue may eventually result in the stuck pipe, wellbore instability, loss of circulation, and inconsistent rheological properties [40, 42, 43].

Several studies were conducted to introduce successful solutions for the sagging issue either by optimizing drilling fluid rheology using anti-sagging agents and rheology modifiers [44–48], reducing the particle size of the weighting material such as micronized barite and ilmenite [37, 49–51], or using a combination of different weighting materials [52–58].

2.4 High-Overbalanced Mud

Oil- and synthetic-based muds are considered as the technical choice to overcome the challenges associated with formations that have highly reactive clays and shale, microfractures, and highly stressed fractured formations. Also, these muds are preferable when drilling low formation pressures with a narrow operating margin between the pore pressure and formation breakdown, which does not allow for increased drilling fluid density and consequently experiences extremely overbalanced pressures. Such formations will result in high-pressure transmission, sloughing shale, loss of circulation, and differential sticking.

But, because of the increased rigid environmental restrictions, further alternative WBDFs development has been encouraged [59, 60]. These alternatives are called high-overbalanced mud, also known as high-performance water-based mud (HPWBM).

The HPWBM is practically used to drill the ultra-deep gas wells and to drill through commingled low and high-pressure formations in one single hole section, such as the

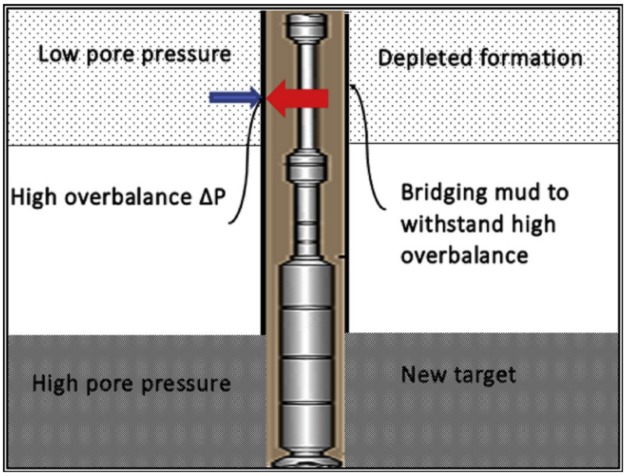

Fig. 3 Drilling through combined depleted reservoir and high-pressure formation using HPWBM. Adapted from Gomaa et al. [61]

combined depleted reservoirs with high-pressure reservoirs, as illustrated in Fig. 3. This special mud bridges along the walls of the well and tolerates the very high differential pressure. In which, the overbalance pressure is within the range of 1000–5000 psi comparing to 200–500 psi for normal overbalance pressure. Using this (HPWBM) will secure the drilling operations whether above or through the target reservoir section, which indeed reduces the total cost of the well. The HPWBM is commonly practiced for gas wells drilling in the middle east. [61, 62].

2.4.1 Composition and Properties

An efficient HPWBM has four criteria to achieve superior drilling performance, these criteria are: (a) low colloidal content; by providing means to chemically flocculate and encapsulate the ultrafine particles to promote higher penetration rate, (b) effective shale inhibitive; by inhibiting the reactive clay to maximize the stability, (c) shear-thinning behavior; for adequate hole cleaning, and (d) non-dispersed system; to reduce solids contamination and build the filter cake with lubricious hydrated polymers instead of being laden with ultrafine drill solids [63]. To fulfill all, not just some, of these high-performance criteria, polymeric additives and commercial sized particulate materials are required.

Table 6 shows an example of an HPWBM recipe with its practical composition and properties using trademarked products.

2.4.2 Drilled Section Characteristics

The HPWBM system is used to combine drilling through natural fractured depleted gas reservoir (such as formation R that described previously) with high-pressure gas reservoirs such as formations S, T, and U.

As described in Fig. 1(v), formation S is composed mainly of sandstone with minor streaks of shale and siltstone, and formation T contains shale with interbeds of dolomite and siltstone, while formation U constitutes mainly of sandstone with minor streaks of shale, siltstone, limestone, and dolomite. The hole size for this section was $5^{7}/_{8}{}''$.

2.4.3 Operational Practices

Using the resilient carbon bridging material (e.g., STEELSEAL®) has a significant advantage when drilling a combination of natural fractured depleted gas reservoirs with high-pressure gas reservoirs. A unique feature of the STEELSEAL® is resiliency, which allows it to mold itself in the tip of the fracture. If the pressure increases further and the fracture opens-up, the STEELSEAL® rebounds itself, thus continuing to plug the fracture completely.

The quantity of each bridging material of the system including STEELSEAL®, BAROFIBRE®, and BARACARB® is determined based on the D_{50} of the particle size distribution (PSD).

After the formulation of the bridging is optimized, the permeability plugging test (PPT) is performed in a specialized filtration-type apparatus to determine the effectiveness of the bridging system. The applied pressure usually is equivalent to the maximum overbalance that will be seen while drilling plus 500 psi.

To maintain the HPWBM and keep it within capable specifications, more attention and manpower are required, which strains the limited crew number.

3 Summary

In this paper, most of the water-based drilling fluid formulations used for onshore gas drilling applications were studied, from both theoretical and practical points of view, and supported by field cases.

The spud mud is an inexpensive mud used for surface hole drilling and composed mainly of flocculated bentonite and water. It is recommended to add detergents with high-viscosity sweeps to avoid the bit balling and help in carrying out the cuttings. Also, in the case of hole instability, the inhibited PHPA mud will be used.

The high-bentonite spud mud is a specialized formula of the spud mud, used as an alternative for invert-emulsion mud, and applied for drilling shallow sections with specific geological horizons and extreme fluid losses. A dilution rate of 20–25 bbl of water and powdered dispersant thinner is practically used to maintain the MBT and gel strength, respectively. That will minimize the effect of surge and swab pressures. It

Table 6 The composition of HPWBM system and its average properties

Material	Unit	Quantity (per bbl.)	Function	Property	Unit	Value
Make-up Water	bbl	As required	Based fluid	Density	pcf	As required
Bentonite	lb/bbl	7.5	Viscosifier	pH	–	9–10
XC Polymer	lb/bbl	0.75	Viscosifier	PV	cP	ALAP
Caustic Soda	lb/bbl	1.45	pH adjustment	YP	lb/100 ft^2	30
NaCl	lb/bbl	20.46	Shale inhibition	10 s Gel/10 min Gel	lb/100 ft^2	6/10 –8/14
Barite	lb/bbl	162	Weighting material	API Filtrate	ml/30 min	< 4
DrisTemp®	lb/bbl	1–3	Fluid loss control	HPHT Filtrate at 300 °F and 500psi	ml/30 min	≤ 14
Resinated Lignite	lb/bbl	4 – 6	Filtration control at HPHT	HPHT filter cake thickness	32^{nd} in	1 – 2
CLAY GRABBER®	lb/bbl	0.75	Flocculant for cutting encapsulation	MBT	lb/bbl equiv.	7.5
CLAY-SYNC™	lb/bbl	0.75	Shale stabilizer	Solid content	vol%	<5
BARACARB25®	lb/bbl	5	Shale stabilizer at high temperature	Cl^-	mg/l	± 40 K
BARACARB50®	lb/bbl	5	Bridging material	Ca^{++}	mg/l	< 400
STEELSEAL 400®	lb/bbl	3	Bridging material	Low-shear yield point (LSYP)	lb/100 ft^2	7–10
STEELSEAL 100®	lb/bbl	3	Bridging material			
STEELSEAL 50®	lb/bbl	4	Bridging material			
BAROFIBRE® super fine	lb/bbl	1	Bridging material			
BARACOR-95®	gal/bbl	0.24	Corrosion inhibitor at high temperature			
Premium Lubricant	gal/bbl	(3% v/v)	Lubricant			

is recommended to switch to PHPA mud at the hole instability. Both spud mud and high-bentonite spud mud should be prepared and pre-hydrated for 4–6 h before a well spud.

To drill unstable shales and hard salt formations, the salt/polymer mud is used for maintaining shale stabilization for both conventional and HPHT conditions. With this mud type, the regular addition of sodium sulfite while drilling is necessary to stabilize the polymers to a bottom hole temperature up to 300 °F. Moreover, to avoid the solids sagging issues associated with drilling HPHT deep gas reservoirs, it is recommended to either uses sag resistance materials, micronized weighting materials, or a combination of different weighting materials.

The HPWBM has a significant advantage when drilling a combination of natural fractured depleted gas reservoirs with high-pressure gas reservoirs, in which a high overbalanced drilling is necessary. The HPWBM is developed from polymeric additives and commercial sized particulate materials by combining mainly resilient graphite carbon, fibrous materials, and sulfonated asphalt. It behaves like oil- and synthetic-based muds in forming a unique system that provides a well-lubricated gauge wellbore.

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