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A New Developed High Performance WBM for Enhancing ROP and Minimizing both ECD and Barite Sagging in Drilling Shaly Wolfcamp Formations

M. Metwally and T. Nguyen, New Mexico Institute of Mining and Technology;
H. Wiggins, Chemplex Solvay Group; M. Gipson, Reliance Energy Company

Abstract

Extended horizontal drilling has become a norm when drilling the shaly Wolfcamp formations to increase hydrocarbon productions. Due to environmental regulations and high cost of Oil Based Mud (OBM), Water Based Mud (WBM) should be considered and studied as a potential alternative drilling fluid. However, designing an appropriate WBM for horizontal wells can result in increasing ECD, barite sagging, bit balling due to shale swelling. These problems increase nonproductive time and drilling cost.

The objective of this study is to develop a high performance WBM formulated by Anionic Friction Reducer (AFR) to prevent bit balling, maintain reasonable Equivalent Circulation Density (ECD), provide better wellbore stability; and mitigating barite sagging. Herschel Bulkley rheological model was used to estimate ECD of an extended horizontal well for both OBM and the formulated WBM.

The results from swelling test, shale dispersion and mud ball immersion tests prove the inhibition capability of formulated WBM with AFR to prevent both shale swelling and dispersion. The Accretion tests show the formulate WBM with AFR is effective to prevent bit balling and this can increase Rate of Penetration (ROP). The viscometer sag shoe test values of the developed WBM in range from 9 to 13 ppg at shear rates from 0.51 to 340 S^{-1} is less than 0.8 ppg. This means developed high performance WBM has a minimal sag tendency in comparison with the one without AFR. The ECD at measured depth of 19,000-ft for the given case study based on hydraulics calculation of 9 ppg WBM with and without AFR are 9.6 ppg, 10.2 ppg, while fracture pressure at this depth is equivalent to 10.5 ppg. Also, the hydraulic calculations reveals that ECD of WBM with AFR is identical as OBM. Therefore, the developed WBM is recommend as an alternative for OBM to maintain wellbore stability, and to increase lateral horizontal section in drilling Wolfcamp formations.

Introduction

The largest province of oil and gas production in the U.S. is the Permian basin. The production from this basin was started in 1921(Ward et al. 1986). The Permian basin has various producing formations such as the Spraberry, Wolfcamp, Bone Spring Yates, San Andres, Clear Fork, Canyon, Morrow, and Devonian. The Wolfcamp and Spraberry formations are considered the second largest oil field with total recoverable reserve of 75 billion barrel oil equivalent (Flumerfelt, 2015). The Wolfcamp formation consists of 4 sections (Wolfcamp A, B, C, and D) with lithology of organic shale and carbonates (US Energy Information Administration, 2018 b).

In 1995, about 75% of wells drilled in the Permian basin, especially Wolfcamp formations, were vertical and around 5% of drilled ones were horizontal. Currently, with increasing of horizontal drilling technology, the percentage of horizontal wells in Wolfcamp formation is 95% in comparison with 4% of vertical wells (Baker Hughes, 2022). This is because horizontal wells lead to maximum contact with reservoir formation and result in increasing hydrocarbon production. This is why, the numbers of horizontal and extended reached wells are continuously growing day after day in the Permian basin (Sharma et al, 2019).

Increasing lateral section in horizontal wells are limited by some technical operational challenges such as torque and drag, the require of high circulation rate, high coefficient of friction, and rise of Equivalent of

Circulation Density (ECD) especially in narrow window between formation and fracture pressure (Allahvirdizadeh, 2015). These challenges can be increased in case of drilling shale formations. Because when shale formation interact with water, the shale can swell, disperse, and stick in bit. These can cause borehole washout, pipe stuck, bit balling, cutting disintegration, and wellbore instability (Patel, 2009). This can increase nonproductive time and limit extension of the lateral section in horizontal wells.

The convention Water Based Mud (WBM) systems was failed to prevent water absorption in the clay. Therefore, the drilling mud industry used Oil Based Mud (OBM) to prevent water interaction with shale. OBM is considered as superior drilling mud for shale inhibition and wellbore stability (Murtaza et al. 2020). In addition, OBM is used to improve thermal stability of rheology under HPHT conditions, enhance Rate of Penetration (ROP), increase lubricity and decrease coefficient of friction while drilling horizontal wells (Katende et al, 2019). On the other hand, there are limits for using OBM in drilling due to its detrimental effect on the environment. Besides, US Environmental protection Agency (EPA) approved stricter regulation criteria for cuttings discharge drilled by OBM. This means more costs associated with OBM cutting discharge (Friedheim et al, 2002).

WBM is considered to be environmental friendly with low cost. Therefore, mud engineers have developed WBM, over the years that can stabilize shale and approach at the same time the performance of OBM. They named it by high performance WBM (Mahrous et al, 2016). A number of methodologies have taken in the consideration for this area, including organic and inorganic salts, glycol, polymer/salt, cationic polymer, silicates, amines, and nanoparticles. However, these additives have some limitations in the applications in drilling mud (Murtaza et al, 2020). Hence, the target of this paper to formulate water based mud using emulsified polyacrylamide to inhibit shale, prevent barite sagging, minimize ECD, and approach performance of OBM.

Materials and Methods

Materials:

The following chemical package was used to formulate the testing fluids:

- Bentonite: used for the initial viscosity, suspension, and fluid loss control
- Starch, and PAC: provided fluid loss reducers
- KCl: salt used for shale inhibition purpose
- Xanthan Gum (XC) polymer: used to provide viscosity
- Soda Ash and caustic soda: Used to control water hardness, and pH, respectively
- Barite: used for controlling drilling fluid density
- Anionic Friction Reducer (AFR): it comprises of anionic acrylamide copolymers emulsified in mineral oil base with density of 9.09 ppg.

Methods:

The methods used in this research are lab experiments and modeling. The available equipment used in this study for preforming lab measurements are mud mixer, pH meter, OFITE 900 rheometer, shale dispersion test, shale accretion test, shale swelling test, and viscometer sag shoe test. OFITE means the manufacturing company, which is OFI Testing Equipment, inc. The pH meter was used to adjust the pH of the formulated WBM. The OFITE rheometer with model of 900 measured automatically shear stress versus different shear speeds at different temperatures up to 200^0 F and ambient pressure.

There are many used techniques to determine shale interaction with the drilling fluids. These techniques are zeta potential, linear swelling test, hot rolling dispersion test, capillary suction test, methylene blue test, accretion test, durability test, and scanning electron microscope. Shale swelling, shale dispersion test, mud ball immersion test, accretion test are used in this study for study shale inhibition.

Shale dispersion test is also known as cutting dispersion test. The clay cuttings are ground and sieved by 20-30 mesh screens. According to API recommendations, the weighted sieved clay cuttings are placed in the aging cell with the formulated drilling fluid in the roller oven for 16 hrs (API 1997). Then shale cuttings are washed and recovered by sieve of 50 mesh. After that, the recovered shale cuttings are heated again in the roller oven for 3 hrs to make sure all water is evaporated. Finally, the recovered shale after heating over the original shale weight is indication of shale recovery percentage. Clearly, higher shale recovery means better shale fluid inhibitor (Jain et al, 2015).

The immersion test is easy visual method to evaluate inhibition performance. The mud ball was created by mixing bentonite with distilled water with mass ratio 2:1. Then, mud balls were immersed for different times in distilled water, and water with shale inhibitors. Finally, the samples were photographed to evaluate visually the swelling, dispersion, and inhibition (Lv et al, 2020).

Swelling test is an easy way to evaluate shale swelling tendency. Mass of 1 g sodium bentonite was added into three flasks with volume 20 ml, and then 10 mL of three different solutions (water, water with KCl, and water with KCl and AFR, respectively) were added. The pH was adjusted between 8.5 and 9.5. The swollen bentonite volume were recorded to evaluate shale inhibition of the formulated solution (Zhao et al, 2017).

Accretion tests have been used extensively to study the sticking tendency of clay in the presence of different drilling fluids on the bit and bottom hole assembly. Accretion test is comparatively unsophisticated and cost-effective method. Accretion was conducted in the laboratory using a steal bar and jar. The test star with placing a clean hollow steel bar in a jar containing 1 barrel of drilling fluid. Then, adding specific grams (W_1) of ¼" bentonite tablets as a shale cuttings is the following step. Then close jar and place it horizontally in the roller oven for 30 minutes at 120 ºF. After 30 minutes, remove the bar from the jar and Photograph the accreted bar for qualitative analysis. Finally remove the sticking solids from steel par and dry them in the oven for 3 hours at 240° F and measure its weight (W_2). The accretion percentage is calculated using the equation 1 (May et al, 2022).

$$Accretion(\%) = \frac{W_2}{\left[\frac{(100-M)}{100}\right] \times W_1} \times 100 \qquad (1)$$

Where:

M: Water content of unexposed bentonite tablets which in our case was 0.1
W_1: Weight of the shale cuttings added initially to the jar
W_3: Weight of sticking shale cutting after drying

Viscometer Sag Shoe Test (VSST) is a test to measure the barite sagging tendency of the drilling fluid (Zamora et al, 2004). This test helps to predict the ability of the formulated WBM to suspend weighting materials and minimize barite sagging. The purpose of the inclined surface of sag shoe is to accelerate settling of the weighting materials and concentrate in the collection well. The VSST procedures are putting the sag shoe inside viscometer plate, add 140 ml from formulated mud inside viscometer plate, heat the mud to 120^0 F ± 2^0 F, rotate viscometer at 100 RPM for 30 min, and extract 10 ml from mud by using syringe with a cannula and record the weight of the mud filled syringe (M_1). Then, the next step is to stop the viscometer after 30 min and extract another 10 ml from the collection well and measure its weight (M_2). The calculation of VSST (ppg) is based on Equation (2)

$$VSST = 0\cdot 833(M_2 - M_1) \qquad (2)$$

The modeling part in this study is based on Hershel-Buckley model to calculate ECD. The Hershel-Buckley model predicts correctly the mud rheology better than the Bingham plastic and the power law rheological models (Folayan et al, 2016). τ_y is the shear stress measured at shear rate of 0.1 S^{-1} using OFITE 900 viscometer. The Hershel-Buckley model parameters (K and n) will be calculated using regression analysis.

$$\tau = \tau_y + K\gamma^n \qquad (3)$$

$$n = \frac{\sum \log(\tau - \tau_y) \sum \log(\gamma) - N \sum (\log(\tau - \tau_y) \log(\gamma))}{(\sum \log \gamma)^2 - N \sum (\log \gamma)^2} \qquad (4)$$

$$\log(K) = \frac{\sum \log(\tau - \tau_y) - n \sum \log(\gamma)}{N} \qquad (5)$$

The following procedures is used to determine the annulus pressure losses and ECD in the field unit.

$$v = \frac{q}{2\cdot 448(d_o^2 - d_i^2)} \qquad (6)$$

Reynolds number of the annulus is calculated using equations 7 and 8.

$$N_{Re} = \frac{4(2n+1)}{n} \left[\frac{\rho v^{(2-n)} \left(\frac{d_o - d_i}{2}\right)^n}{\tau_y \left(\frac{d_o - d_i}{2v}\right)^n + K \left(\frac{2(2+1)}{nC_a^*}\right)^n} \right] \qquad (7)$$

$$C_a^* = 1 - \left(\frac{1}{n+1}\right) \frac{\tau_y}{\tau_y + K \left\{ \frac{2q\,(2n+1)}{n\pi \left[\frac{d_o}{2} - \frac{d_i}{2}\right] * \left[\left(\frac{d_o}{2}\right)^2 - \left(\frac{d_i}{2}\right)^2\right]} \right\}^n} \qquad (8)$$

The critical Reynolds number of the annulus is calculated using equations 9, 10 and 11.

$$N_{Rec} = \left[\frac{8(2n+1)}{ny}\right]^{\frac{1}{1-z}} \qquad (9)$$

$$y = \frac{\log(n) + 3\cdot 93}{50} \qquad (10)$$

$$z = \frac{1\cdot 75 - \log(n)}{7} \qquad (11)$$

If $N_{Re} < N_{Rec}$, then the flow is laminar and pressure loss is calculated using equation 11.

$$\Delta P = \frac{4K}{14400(d_o - d_i)}\left\{\left(\frac{\tau_y}{K}\right) + \left[\left(\frac{16(2n+1)}{nC_a^*(d_o - d_i)}\right)\left(\frac{q}{\pi(d_o^2 - d_i^2)}\right)\right]^n\right\}\Delta L \quad (12)$$

If $N_{Re} > N_{Rec}$, the flow is turbulent and pressure loss is calculated using equation 13.

$$\Delta P = \frac{f_a\, q^2\, \rho}{1421 \cdot 22(d_o - d_i)\left(d_o^2 - d_i^2\right)^2}\Delta L \quad (13)$$

$$f_a = y(C_a^* * N_{Re})^{-z} \quad (14)$$

$$ECD = \rho_m + \frac{pressure\ losses}{0 \cdot 052 \times TVD} \quad (15)$$

Results and discussions

The swelling test for I gm bentonite had volume of 2.6 ml at time zero. This volume was added to different solutions as the results of this test with time are shown in (Fig. 1). It is clear that water absorb in bentonite and make it swelling as the volume of bentonite increase from 2.6 ml to 6 ml after 3 hr. on the other hand, the KCl with water solution has less swollen volume than water solution and maximum expansion volume of bentonite after 3 hours was around 3.7 ml. Nevertheless, when 0.5 lbm/bbl AFR was added to the solution of water with KCl, AFR prevent bentonite from swelling and its expansion volume became constant after 0.5 hour at 3 ml. this means after AFR interact with shale, it prevent water absorption quickly and inhibit swelling and this can lead to stabilize shale during drilling.

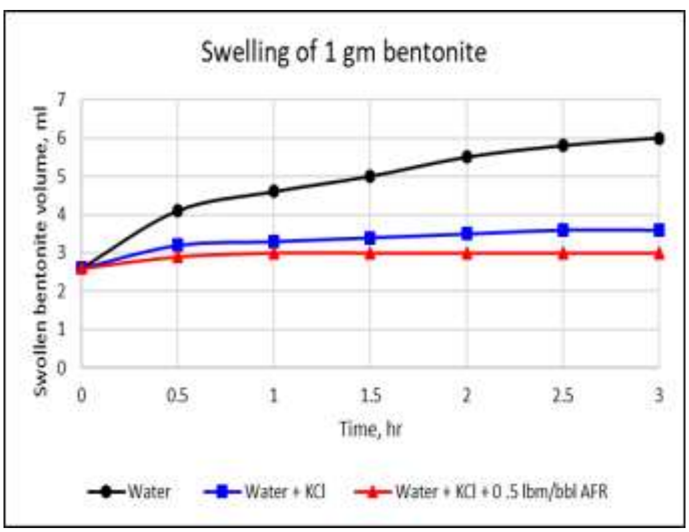

Figure 1: swollen bentonite volume in different solutions

Shale dispersion test is another way to evaluate shale stabilization capability of proposed shale inhibitor. Dispersion tests were done to determine percentage of shale recovery when using formulated WBM with 0.25 and 0.50 lbm/bbl of AFR. The mud formulation of the developed mud with and without AFR is mentioned in (Table 1). The shale cuttings used in the test were obtained from the Wolfcamp shaly formation. The results of shale recovery from this test were illustrated in (Table. 2).The shale recovery were 98.7 and 99.7% when using AFR of .25, and 0.50 lbm/bbl, respectively. This means AFR prevent shale dispersion by encapsulating shale surface and prevent water shale interaction. Hence, the formulated WBM with AFR is capable to prevent shale swelling and dispersion.

Table 1: Test matrix to the formulated WBM with and without AFR

Step 1			Step 2		
pH(8.5-9.5)			pH(8.5-9.5)		
Additives	Quantities	Unit	Additives	Quantities	Unit
Water	1	bbl	Water	1	bbl
Bentonite	8	lbm/bbl	Bentonite	0	lbm/bbl
NaOH	0.5	lbm/bbl	NaOH	0.5	lbm/bbl
AFR	0	lbm/bbl	AFR	0.25 and 0.5	lbm/bbl
Starch	3	lbm/bbl	Starch	3	lbm/bbl
PAC-L	1	lbm/bbl	PAC-L	1	lbm/bbl
XC polymer	0.75	lbm/bbl	XC polymer	0.75	lbm/bbl
KCl	17.5	lbm/bbl	KCl	17.5	lbm/bbl
Barite	As required	lbm/bbl	Barite	As required	lbm/bbl

Table 2: Shale dispersion test results for WBM with and without AFR

Mud Type	Shale Recovery (%)
WBM with 0 lbm/bbl AFR	90
WBM with 0.25 lbm/bbl AFR	98.7
WBM with 0.50 lbm/bbl AFR	99.7

Another Test to evaluate shale inhibition of the developed WBM with AFR is the immersion test. This test is based on taking physical pictures of the mud balls after immersed in water, water with 5% KCl, and water with 5% KCl and 0.07% AFR. The pictures of mud balls were taken after 0 hr, 24 hr, and 48 hr as shown in (Fig. 2).It is clear that mud ball in water hydrated with water and swelled. After swelling of shale in water, the ball started to crack. But, the mud ball in water with 5% KCl showed cracks or dispersion without swelling. The dispersions increased with time.

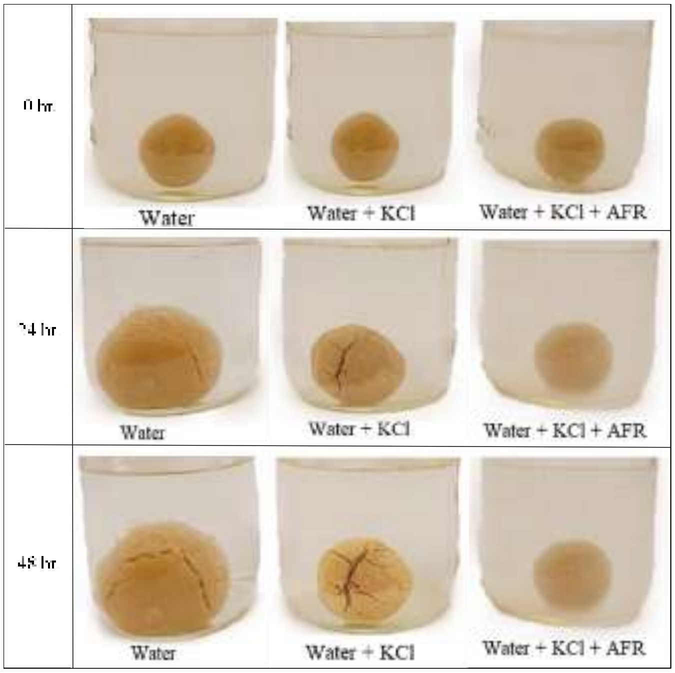

Figure 2: Pictures of Mud Ball after immersed in different fluids at different times

On the other hand, no any swelling and cracks appeared in the solution of water with 5% KCl and 0.07% AFR. The mechanism behind that is absorption of water inside mud ball for solution of water only. The swelling occurred due to water absorption and leads to volume increase. The cement bond between clay particles decreased and consequently the compressive strength reduced. Cracking started to appear. Hence, both swelling and dispersion of shale happened in case of water solution without any additives.

In the water solution with 5% KCl, there was cracking or dispersion without swelling. KCl salt was sufficient to prevent swelling. In this case, KCl dehydrated water and prevent water absorption by fixation mechanism. This decreased radial stress and increased hoop stress around mud ball and result in shear failure. Subsequently, there will be washout problems due to this dispersion if KCl is used only as a shale inhibition.

Alternatively, the mud ball maintained its spherical shape after being immersed in a solution with 0.07% AFR for 48 hr. This means AFR adsorbed on mud or clay ball, formed thin or protective layer, and prevent water to interact with shale. This protective layer increased radial stress and minimized difference between hoop stress and radial stress and this helps prevent cracking or dispersion. It is become clear from swelling test, dispersion test, and immersion test; the developed WBM with AFR can enhance shale inhibition and prevent both shale swelling and dispersion.

Bit balling is the sticking of cuttings to the bit surface while drilling through gumbo clays, water reactive clays, and shale formation.Bit balling can cause several problems such as reduction in ROP and surface torque, increase in stand pipe pressure (Stefano et al, 2008).Personnel may eventually need to pull out of hole the bottom hole assembly in order to clear the balling issue at the bit. The bentonite tablets used in this study has Cation Exchange Capacity (CEC) is 40 meq/100 gm), which means it has high swelling capability. The accretion tests were performed using different clay weights (25, 50, 75, and 100 gm. These additives were put in different WBM formulations. Fig. 3 shows clay accretion profile after immersed in WBM without KCl and AFR. It is clear that clay sticking increased with adding clay tablets. This shale accretion can lead to bit balling and decrease ROP. Oppositely, WBM with KCl and without AFR has lower shale sticking in comparison with formulating WBM without both KCl and AFR as demonstrated in Fig. 4. Unfortunately, KCl Mud alone was seems to not sufficient to prevent bit balling when shale cutting increased in the annulus. This appeared when shale tablets increased from 75 gm to 100 gm. At the end, this formulating WBM with KCl only will have low ROP if it is used to drill active selling shale formation.

Figure 3: Clay accretion profile in WBM without both KCl and AFR

In contrast, when AFR was added to the formulated WBM with KCl, shale did not accrete in steel bar even when the added shale amount raised from 25 gm to 100 gm as shown in Fig. 5. Therefore, the formulated WBM with AFR was capable to prevent shale sticking and bit balling and increase ROP. The mechanism behind the ability of AFR to preclude bit balling is the manufacturing itself of AFR. This AFR is emulsified copolymer which means it is synthetized in presence of surfactant. This surfactant will form between the clay surface and solid

Figure 4: Clay accretion profile in WBM with KCl and without AFR

Figure 5: Clay accretion profile in WBM with KCl and AFR

bar and inhibit sticking. Hence, the accretion percentage of shale in case of WBM with AFR was less than 1% (Fig. 6), which means that AFR not only inhibit shale swelling and dispersion, but also able to prevent shale accretion and minimize bit balling problem.

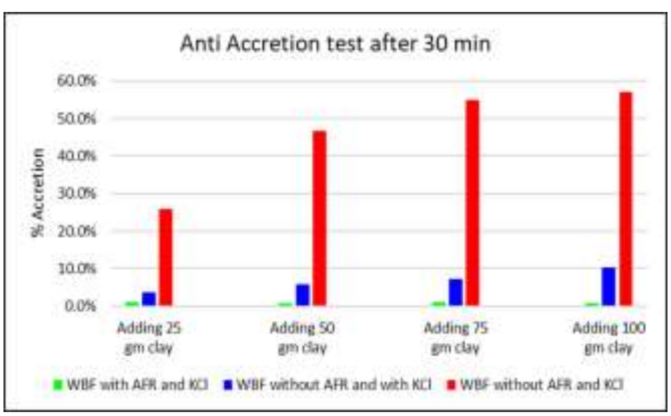

Figure 6: Accretion percentage of the formulated WBM with and without AFR

Fluid rheology of the two formulated WBM with AFR were measured at different temperatures range from 120° to 180° F. (Fig. 7 and Fig. 8) illustrate the shear stress versus shear rate. The formulated mud with AFR of concentration ranging from 0.25 to 0.50 lbm/bbl showed shear thinning behavior. It was obvious that measured shear stress increased with increased temperature. In addition, WBM with 0.25 and 0.50 lbm/bbl had thermal stability and high resistant to viscosity thermal degradation. This thermal stability was based on interaction between AFR and bentonite in the formulated mud and this interaction increased with temperature rising. The formed hydrogen bond between amide group on AFR backbone and oxygen in the bentonite surface is the main interaction behind this temperature stability. In addition, this interaction is responsible for the encapsulation of AFR to clay surface and stabilize reactive shale.

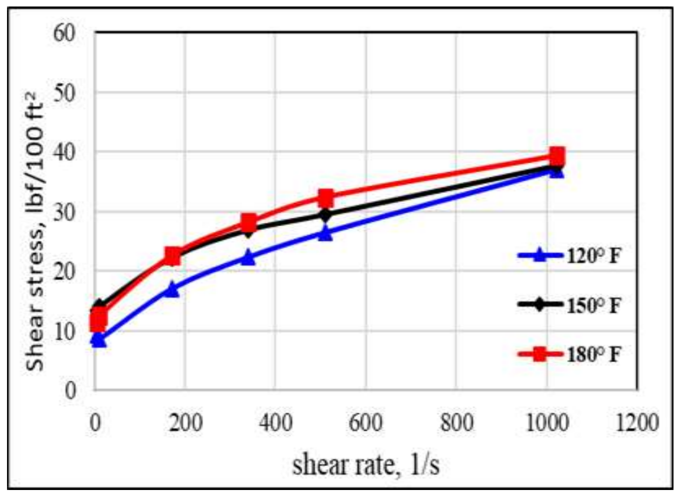

Figure 7: WBM with 0.25 lbm/bbl AFR

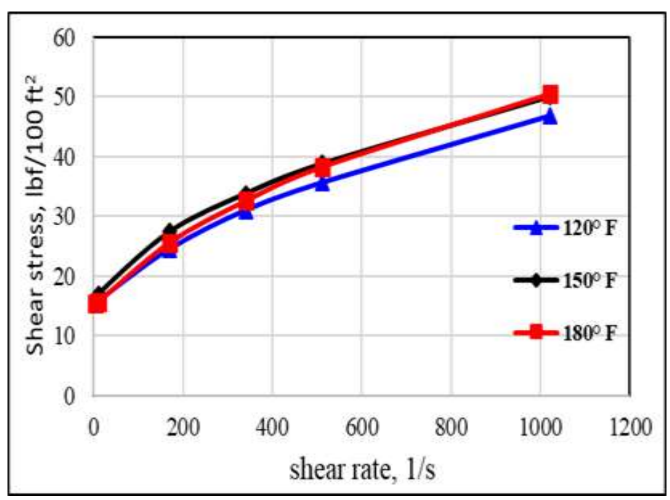

Figure 8: WBM with 0.50 lbm/bbl AFR

The formulated WBM with AFR showed good shale inhibition performance and thermal stability of fluid rheology. The appropriate mud system should minimize barite sagging. The barite sagging is a severe problem in horizontal wells. Barite sagging means the separation of barite (weighting material) from liquid phase and settle down. Barite sagging can cause variations in mud density. This variations lead to increase risks to have kick or well control problem (Al-Mujalhem et al, 2022).

Therefore, the mud with good rheology should mitigate barite sagging. The formulated WBM with and without AFR were tested by using VSST to determine sag tendency. The VSST test procedures were previously mentioned in the experimental apparatus section. WBM with different densities ranged from 9 to 13 ppg were formulated and VSST were calculated using equation 4. When VSST value is less than 1 ppg, the drilling fluid has minimal sagging tendency (Aldea et al 2001). However, when VSST value is higher than 1.6 ppg, there is possibility to have sag problems (Bern et al, 2010).

The results of VSST are shown in (Fig. 9, Fig. 10). WBM with AFR has less VSST in comparison with WBM without AFR for all mud density ranged from 9 to 13 ppg with different shear rates. This means interaction between AFR with bentonite in presence of the electrolyte formed and enhanced this gel structure. Hence, the developed WBM with the AFR able to suspend barite-weighting material and minimize sagging problem.

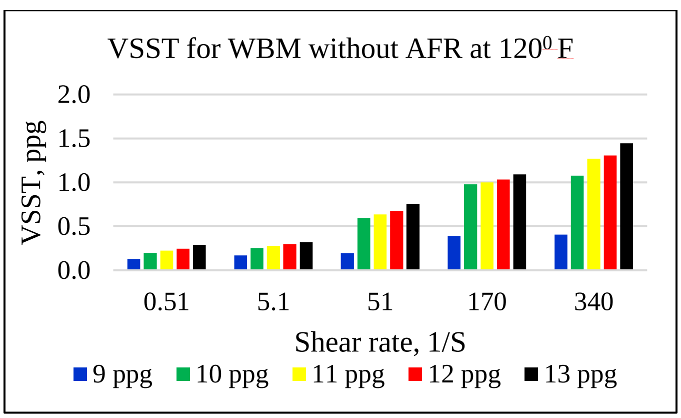

Figure 9: VSST of WBM without AFR

ECD is important drilling parameters especially in drilling formation with narrow windows between pore and fracture pressures. In this formation, ECD should be control to prevent loss of circulation problems. Hence, it is required to ECD of the fluid with and without AFR and comparison these results with OBM. Fig. 11 show the sketch well which was drilled in the midland basin. The

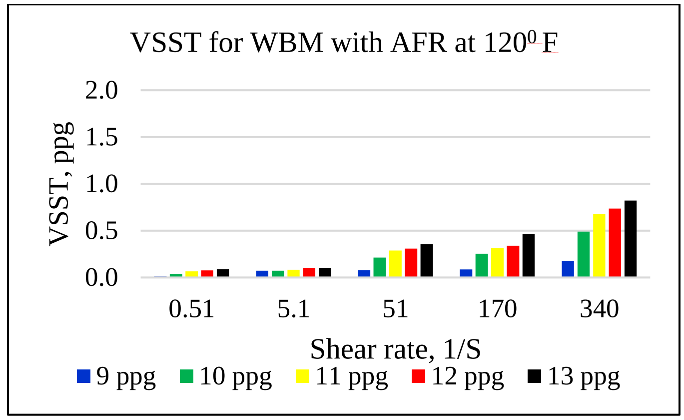

Figure 10: VSST of WBM with AFR

hole of 8.5 inch was drilling in Spraberry shale formation using OBM and its properties was measures at 120° F and mentioned in Fig. 11. In addition, the circulation rate in 8.5 inch hole was 846 gallon per minute. The Hershel-Buckley model parameters (τ_y, K and n) at 120° F are mentioned in table 3.

Table 3: The value of Hershel-Buckley parameters for different formulated muds

	WBM without AFR	WBM with AFR	OBM
τ_y (lbf/100 ft^2)	2.8	9.6	5.35
n	0.825	0.28	0.44
K (lbf.S^n/100 ft^2)	0.108	2.05	1.17

The calculated ECD using Hershel-Buckley model for different drilling fluids were illustrated in Fig. 12. The ECD for WBM with AFR is less the ECD of WBM without AFR in the horizontal deviated section. In addition, the curve of ECD for WBM with AFR is identical as OBM. This means AFR is able to minimize ECD for WBM and has near ECD performance for OBM. Therefore, AFR can help in minimize pressure drop in the annulus and decrease pump capacity required on the surface. Finally, this can lead to increase the lateral section of the horizontal wells.

The developed WBM by AFR enhance shale stabilization and inhibition as it prevents shale swelling, dispersion, and accretion. As AFR with WBM able to be adsorbed on shale surface and form thin layer to prevent water interaction with shale. By this way, the formulated WBM with AFR mitigate bit balling problem and increase ROP. In addition, the developed WBM with AFR has stabilized rheology at temperature up to 180^0 F. Besides, AFR has vital role for suspending weighting materials and

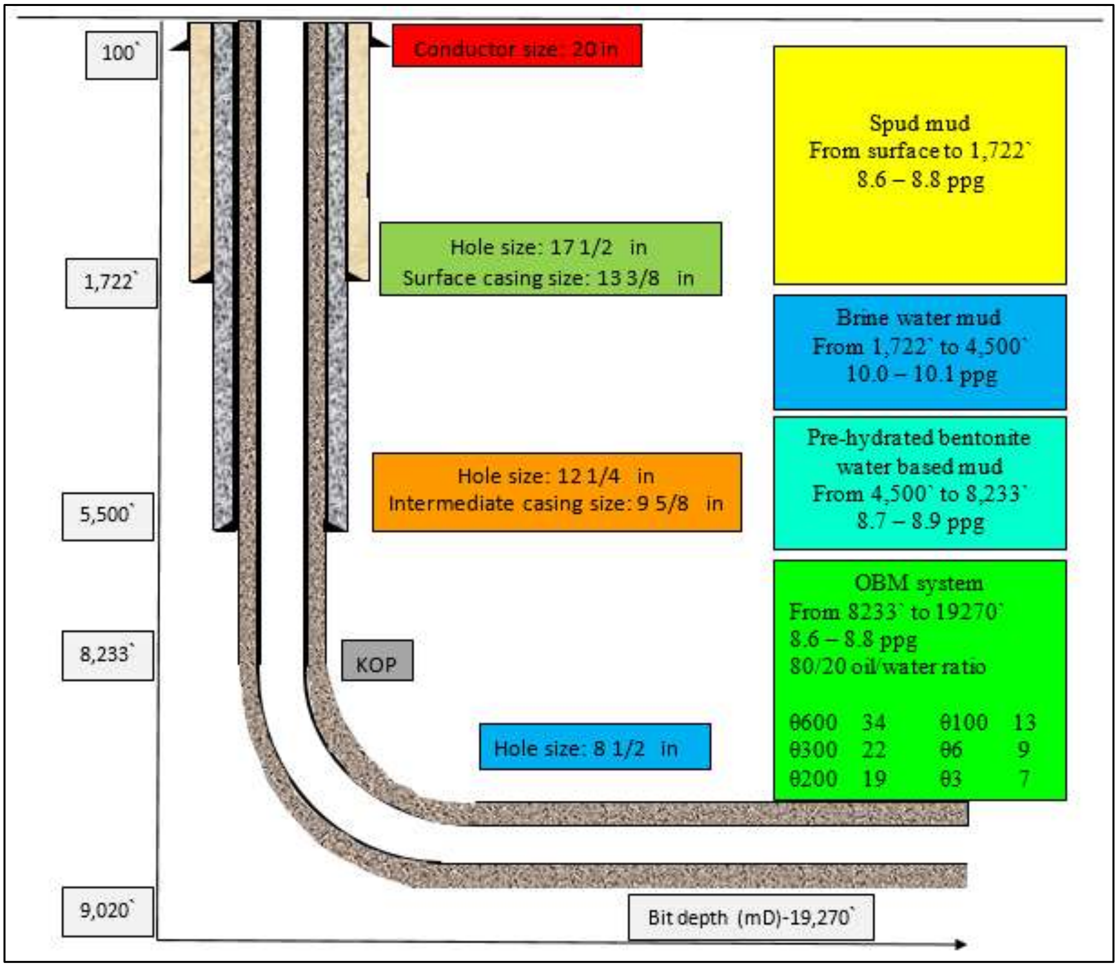

Figure 11: Wellbore sketch with casing sizes and used mud

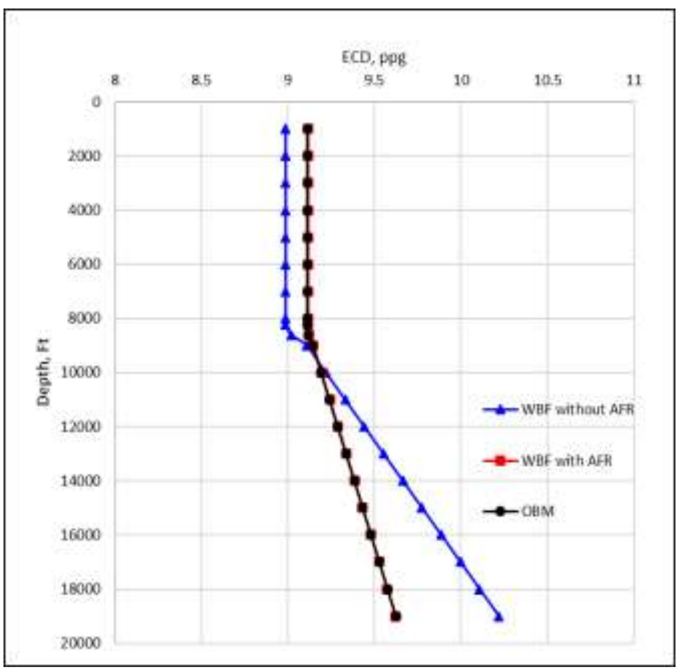

Figure 12: ECD calculated using Hershel-Buckley model for different drilling fluids

mitigating barite sag problem. In addition, AFR has a significant cause for decreasing ECD for the formulated WBM and approach performance of OBM. Due to the environmental regulation for limiting use of OBM and additional cost for discharge of OBM cuttings, the new formulated WBM with AFR may be considered as a promising alternative to replace OBM in drilling Wolfcamp formations in the Permian Basin.

Conclusion

This paper focused experimentally on investigating the ability of using AFR with WBM as a shale inhibition, barite sagging mitigation, and enhancing ROP. Besides, it concentrated on how the formulated WBM with AFR minimize ECD and compare the findings with OBM by using Hershel-Buckley model. The following conclusions are drawn from the study:

- Shale Dispersion, Mud ball immersion, and swelling tests proved the success of AFR as a shale inhibitor in WBM to prevent shale swelling and dispersion.

- Shale recovery of the formulating WBM with AFR is 98.5% and 99% when adding AFR with concentrations of 0.25 and 0.5 lbm/bbl, respectively
- Encapsulation is the dominant shale inhibition mechanism of AFR
- The AFR with concentration from 0.25 lbm/bbl to 0.50 lbm/bbl in drilling mud overcome thermal degradation problem for the mud rheology up to 180° F.
- The Accretion tests show the formulate WBM with AFR is effective to prevent bit balling and increase ROP.
- Adding AFR to WBM helps suspending weighting materials and mitigating barite sag
- The ECD at measured depth of 19,000 ft for the given case study based on hydraulics calculation of 9 ppg WBM with and without AFR are 9.6 ppg, 10.2 ppg, respectively.
- The formulated WBM could be used to replace oil based drilling fluids when drilling long lateral sections

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Abbreviations

N_{Re}	Reynold Number
N_{Rec}	Critical Reynold Number
d_O	Outside diameter
d_i	Inside diameter
τ_y	Yield stress
AFR	Anionic Friction Reducer
API	American Petroleum Institute
bbl	Barrel
ECD	Equivalent Circulation Density
Ibm	Pound mass
K	The consistency index
n	The Flow index
OBM	Oil Based Mud
OFITE	OFI Testing Equipment®
PAC	Polyanionic Cellulose
ppg	Pound per gallon
ROP	Rate of Penetration
S	Second
VSST	Viscometer Sag Shoe Test
WBM	Water Based Mud
XC	Xanthan gum

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