Characterization of Microbubble-Based Drilling Fluids: Investigating the Role of Surfactants and Polymers

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ABSTRACT: *Colloidal Gas Aphrons (CGA), consist of gas bubbles with diameters ranging from 10 to 100 micron, surrounded by a thin aqueous surfactant film. This fluid combines certain surfactants and polymers to create the systems of microbubbles. The function of surfactant in CGAs is to produce the surface tension to contain the aphrons. Also, a biopolymer needs to be considered in the formulation as a viscosifier as well as a stabilizer. The aphron-laden fluid appears to be particularly well suited for drilling through depleted zones. The unique feature of aphron based fluids is to form a solid free, tough, and elastic internal bridge in pore networks or fractures to minimize deep invasion using air microbubbles. This microenvironment seal readily cleans up with reservoir flow back as production is initiated, thereby reducing cost associated with stimulation processes. This paper presents a comprehensive, comparative study of rheological behavior and filtration properties of CGA based drilling fluids with various concentrations of polymer and surfactant. Laboratory evaluations showed that the CGA based fluid is one of the ideal engineering materials which can control and kill the loss circulation, save cost and increase productivity in which rheological characteristics and filtration properties of them are greatly influenced by the level of polymer and surfactant concentration.*

KEYWORDS: *Colloidal gas aphron; Microbubble; Shear-thinning; Biopolymer; Rheology; Microscopy.*

INTRODUCTION

Aphrons are colloidal dispersions of microbubbles. An aphron is made up of a core that is often spherical of an internal phase encapsulated in a thin shell. In the case of a gaseous core, this structure is called colloidal gas aphron [1]. Likewise, when the internal core is a liquid, normally oil, it is called colloidal liquid aphron [2]. Finally, aphrons with cores formed by Water-in-Oil (W/O) emulsion are called colloidal emulsion aphrons [3]. Drilling fluids containing CGAs in aqueous (water) medium have been successfully employed in oilfields to drill through depleted reservoirs or formations which previously had experienced uncontrollable losses and high incidence of differential sticking [4-9]. The potential of aphrons as components of drilling fluids rests in their

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ability to form a solid free, tough, and elastic internal bridge in pore networks or fractures to minimize deep invasion by means of air microbubbles. This micro-environment seal readily cleans up with reservoir flow-back as production is initiated, thereby reducing cost associated with stimulation processes [10, 11]. In hundreds of wells in diversified applications worldwide, the aphron fluid technology has proven to be a viable alternative to more costly, under-balanced drilled or oil-based muds. This fluid technology has been proven to bring many operational benefits such as eliminating loss circulation problems, reducing drilling time, eliminating intermediate casing, successful running electrical logs, and improving cement jobs while simplifying completions and providing rapid cleanup [7].

For aphrons to be used in drilling fluids, they need to have a certain degree of stability. For this reason, the encapsulating film must have certain properties: (1) the film must not be too thin, otherwise it will tend to break under pressure; and (2) the protective layer must have a minimum viscosity. Aphron stability is determined by the rate of mass transfer between the viscous water shell and the bulk phase. This transfer is known as the Marangoni effect [1]. If the mass transfer rate is high, aphrons will be unstable. By viscosifying the water through the addition of a polymer the rate of mass transfer is reduced to a point where the aphron structure is stabilized [5].

This fluid combines certain surfactant and polymers to create a system of microbubbles. Polymer is one of the most important components of CGA based drilling fluids. *Brookey* [4] found a Xanthan Gum (XG) biopolymer to be the best for stabilizing the CGAs and increase the low shear rate viscosity (LSRV) which encouraged good invasion control, cuttings suspension, and hole cleaning. *Ramirez et al.* [6] recommends the use of a biopolymer blend which is a mixture of nonionic polymers that generate high viscosity at low shear rates. Growcock at al.[12] mentions the use of clay/polymer blends to act as a viscosifier. *Bjorndalen* and *Kuru* [13] used the XG biopolymer as a viscosifier and aphron stabilizer. *Spinelli et al.* [14] prepared the base fluids for aphronization by mixing the organic phase at different concentrations of organophilic clay and viscosifiers.

Surface active agent or surfactant needs to be considered in the formulation of CGA based fluids to produce the surface tension to contain the aphron as it is formed, build the multilayer bubble wall, and create interfacial tension to form a non-bonding network capable of bridging openings in permeable and fractured formations [4]. The surface activity and aggregation behavior of the surfactant affects the stability and also other physico-chemical properties of generated microbubbles. Therefore, selection of a suitable surfactant is important for the generation of microbubbles with the desired rheological and filtration properties [15].

Rheological properties are used to design and evaluate the hydraulics and to assess the functionality of the mud system. The rheology of drilling fluids affects many aspects for their performance and is critical to the safe and successful execution of a well [16]. In order to characterize the non-Newtonian behavior of drilling fluids, drilling hydraulic calculations require a rheological model [17]. Modeling of fluid behavior is of extreme importance to predicting downhole performance for efficient, safe and economical drilling operation [18]. Thus, proper understanding and application of rheological principles is vital in evaluating drilling fluid behavior are in solving problems of hole cleaning, hydraulic calculations, suspension of cuttings, and drilling fluid treatment. Several models have been developed which attempt to better describe the rheological behavior of drilling fluids. However, most drilling fluids are too complex to allow a single set of equations to be used in determining their behavior under all conditions. For the purpose of this study, eight most used of these rheological models (two and three parameters) will be investigated here and a comparison will be made among them.

This paper presents an investigation of the fluid's stability and rheological behavior.

EXPERIMENTAL SECTION

Polymers

Xanthan gum polymer (XG), a high-molecular-weight natural polysaccharide, was used as viscosifier as well as stabilizer. XG is a common drilling fluid additive for controlling fluid loss, and viscosity improvement in the formulation of both oil-based and water-based drilling muds [19, 20]. It hydrates rapidly in cold water without lumping to give a reliable viscosity, encouraging its use as thickener, stabilizer, emulsifier, and foaming agent [21]. It has an excellent tolerance to the changes of temperature, acid, and alkaline. Meanwhile, it is notgreatly affected by salinity and can be used in saturated salt water [22]. In response to environmental concerns, XG presents good properties for drilling muds application [23].

Chemically, guar gum is a polysaccharide composed of the sugars galactose and mannose. The backbone is a linear chain of β 1,4-linked mannose residues to which galactose residues are 1,6-linked at every second mannose, forming short side-branches.

Surfactants

In order to produce stable microbubbles, a surfactant needs to be considered in formulation. Two types of surfactants have been chosen for this study: Cetrimonium bromide (CTAB), a cationic surfactant and Sodium dodecyl sulfate (SDS), an anionic surfactant.

Preparation of base fluids and aphron based fluids

Polymer (either of XG or guar gum) –water mixture was used as the base drilling fluid. The base fluid was prepared by mixing the biopolymer at different concentration in 350 mL water (one laboratory barrel). The solutions all were agitated for 20 minutes at speed of 10,000 rpm to avoid formation of local viscosified agglomerates.

A microbubble suspension is generated by using a spinning disc type generator with a surfactant solution. In this study, the microbubble generator comprised of a 1-litre beaker and a central agitator. The agitator consisted of a 3-cm diameter spinning disk mounted at the end of a shaft connected to an electrical motor. The base fluid and surfactant mixture was then homogenized for 120 seconds at the speed of 8,000 rpm.

Visualization of aphrons

Immediately following the generation of aphron bubbles, the sample was imaged by using a digital video camera which was then attached to an optical microscope. Fig. 3 shows typical microscopic pictures of CGA based drilling fluids with different degree of magnification. The micro structure model of “one core, two layers, and three membranes” is observable in Fig. 1 which perfectly matches with the structure model proposed by Sebba.

Rheological Characterization of the fluids

In this section of fluid characterization, a Fann 35 viscometer was used to measure the fluid’s rheological properties. The data shown on the viscometer screen are then converted to shear stress and shear rate by using appropriate conversions. Based on the rheology theory of Bingham plastic fluid, the apparent viscosity, plastic viscosity and yield point and based on the rheology theory of Power Law fluid the consistency coefficient and the behavior index of aphronized drilling fluids and their base fluids were calculated from Fann dial readings using formulas from API Recommended practice of Standard procedure for field testing drilling fluids.

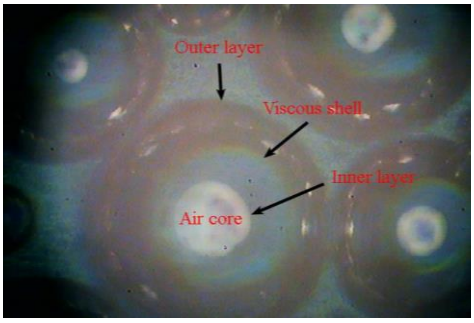

Fig. 1: Microscopic image of aphron microbubbles.

Filtration reduction evaluation of the fluids

The rate of fluid filtration into the reservoir rock is one of the most critical parameters that need to be controlled carefully during drilling, completion and stimulation operations. The problem becomes even more critical when drilling with water based fluids where the fluid remains in contact with the pay zone for a long period. API filtration loss tests were conducted using a standard filter press at 100 psi pressure and room temperature. The final volume of filtrate after 30 minin ml was noted as API filtrate.

Stability of the CGAs

Stability of CGAs is crucial to application of microbubbles for effective bridging/blocking ability during drilling operation. Stability of CGAs is investigated by analyses through drainage rate measurement over time. All the experiments were done in atmospheric pressure. To conduct static drainage tests, initially, 400 mL of the freshly prepared CGA based fluid is poured into a graduated cylinder. With time, total height (H_t) of the solution will decrease. In addition, the base fluid will drain out of the CGAs laminar region and a drained height (H_t) will form at the bottom of the cylinder. The height of total fluid volume, as well as, the drained volume is recorded during the test time.

Table 1: Effect of surfactant type and concentration on rheological properties of CGA based drilling fluids.

Base Fluid Formulation	Surfactant	Surfactant concentration (gr/350 cc)	Apparent viscosity (cp)	Plastic viscosity (cp)	Yield strength (lb/100 ft^2)
XG (2 lb/bbl)	SDS	0.5	32	9	46
XG (2 lb/bbl)	SDS	1.0	37.5	11	53
XG (2 lb/bbl)	SDS	1.5	40.5	12	57
Guar Gum (2 lb/bbl)	SDS	0.5	25	5	57
Guar Gum (2 lb/bbl)	SDS	1.5	30	7	46
XG (2 lb/bbl)	CTAB	0.5	28	7	42
XG (2 lb/bbl)	CTAB	1.5	37.5	11	53
Guar Gum (2 lb/bbl)	CTAB	0.5	24.5	6	37
Guar Gum (2 lb/bbl)	CTAB	1.0	29.0	9	40
Guar Gum (2 lb/bbl)	CTAB	1.5	30.5	10	41

RESULTS AND DISCUSSION

Effect of polymer and surfactant concentration on the rheology

For acceptable drilling fluids they must have abilities to clean the well, suspend the cuttings and weighting materials, keep the well wall stable and make sure it's safe while tripping. CGA based drilling fluids meets these requirements. The rheological properties of CGA based drilling fluids at different surfactant types and concentrations concentration are tabulated in Table 1. Plastic viscosity varies from 24 to 40 cp while the ordinary solid free water based drilling fluids with the same density have much lower values of plastic viscosity. Also, yield strengths of aphron based drilling fluids were high. The apparent viscosity, plastic viscosity and yield point f aphron based drilling fluids increased with the increase of the concentration of surfactant. Increasing surfactant concentration means there are more surfactant in the system to stabilize large amount of interfacial area which in turn, lead to formation of more stable microbubbles. This increase in the concentration of microbubbles increases the intermolecular forces which lead to increase in above mentioned rheological parameters.

Effect of polymers and concentrations on the rheological characteristics of aphron fluids are reported in Table 2.

Effect of concentration of Xanthan Gum (XG) biopolymer on the rheology of aphronized drilling fluids also studied. The apparent viscosity, plastic viscosity, and yield point, increased with the increase of XG concentration shown in Table 2. The increase of above rheological parameters is due to the increase of effective viscosity of the base fluid with increasing XG concentration.

Performance of microbubbles in filtrate reduction

The effect of presence of microbubbles in drilling fluids on filtration properties was found to be significant. Sixteen different formulations of aphron based fluids were prepared. Table 3 reports the formulation as well as API filtration volumes.

In order to investigate the filtration properties of aphrons for SDS surfactant concentration, sample numbers of 3, 9, 10, 13, 14 are considered. On the other hand, samples of 7, 11, 12, 15, 16 are used for examining the CTAB effect and performance. The filtration loss and spurt loss decreased with increasing surfactant concentration. This can be attributed to the majority of air microbubbles with increasing surfactant concentration, which means more bubbles are available to accumulate in front of pores and limit the filtration of fluid into the formation. Aphronized drilling fluids with the higher concentration of microbubbles are more efficient at the initiation of filtration test, because system with the higher surfactant concentration have higher concentration

Table 2: Effect of polymers and concentrations on rheological properties of CGA based drilling fluids

Base Fluid Formulation	Polymer	Polymer concentration (g/350 cc)	Apparent viscosity (cp)	Plastic viscosity (cp)	Yield strength (lb/100 ft^2)
SDS (1 lb/bbl)	XG	1.0	33.5	8	51
SDS (2 lb/bbl)	XG	1.5	36	10	52
SDS (2 lb/bbl)	XG	2.0	37.5	11	53
SDS (2 lb/bbl)	XG	2.5	40	12	56
CTAB (2 lb/bbl)	Guar Gum	1.0	23.5	6	35
CTAB (2 lb/bbl)	Guar Gum	1.5	25	7	36
CTAB (2 lb/bbl)	Guar Gum	2.0	29	9	40
CTAB (2 lb/bbl)	Guar Gum	2.5	31	10	42

Table 3: Effect of surfactants and concentrations on rheological properties of CGA based drilling fluids

No.	Polymer formulation	Surfactant formulation	API Filtration volume (mL)
1	XG (1.0 lb/bbl)	SDS (1.0 lb/bbl)	60
2	XG (1.5 lb/bbl)	SDS (1.0 lb/bbl)	37.5
3	XG (2.0 lb/bbl)	SDS (1.0 lb/bbl)	22.5
4	XG (2.5 lb/bbl)	SDS (1.0 lb/bbl)	13.5
5	Guar Gum (1.0 lb/bbl)	CTAB (1.0 lb/bbl)	77.5
6	Guar Gum (1.5 lb/bbl)	CTAB (1.0 lb/bbl)	55
7	Guar Gum (2.0 lb/bbl)	CTAB (1.0 lb/bbl)	42.5
8	Guar Gum (2.5 lb/bbl)	CTAB (1.0 lb/bbl)	30
9	XG (2.0 lb/bbl)	SDS (0.5 lb/bbl)	30
10	XG (2.0 lb/bbl)	SDS (1.5 lb/bbl)	18
11	XG (2.0 lb/bbl)	CTAB (0.5 lb/bbl)	35
12	XG (2.0 lb/bbl)	CTAB (1.5 lb/bbl)	25
13	Guar Gum (2.0 lb/bbl)	SDS (0.5 lb/bbl)	42.5
14	Guar Gum (2.0 lb/bbl)	SDS (1.5 lb/bbl)	35
15	Guar Gum (2.0 lb/bbl)	CTAB (0.5 lb/bbl)	50
16	Guar Gum (2.0 lb/bbl)	CTAB (1.5 lb/bbl)	40

of microbubbles with greater average diameter of aphrons which promotes effective sealing ability. The results indicated that there is a strong positive effect of aphron microbubbles on reducing the amount of fluid loss into the formation. Effect of increasing polymer concentration on the API filtration loss of aphron based fluids is also shown in this table. API filtration losses decreased increasing the polymer concentrations. Effect of incrasing polymer concentration is beneficial in two ways: first, it increases the aphron stability and makes it as a tough material and from the other point polymer also thicken the fluid in the way that restricts the fluid invasion into the formation.

Static drainage tests

The stability of CGA-based fluid is defined as its ability to resist change in bubble size, liquid content or degree of dispersion. As a result of density difference between aphrons and bulk solution, the bubbles cream pward and the liquid drains downward. In order to investigate the homogeneity of CGA-based fluids with time static drainage experiments were conducted. The experimental results of drainage tests are plotted in Fig. 2-7.

The concentration of XG in the formulation was found to have a great influence on stability of CGA

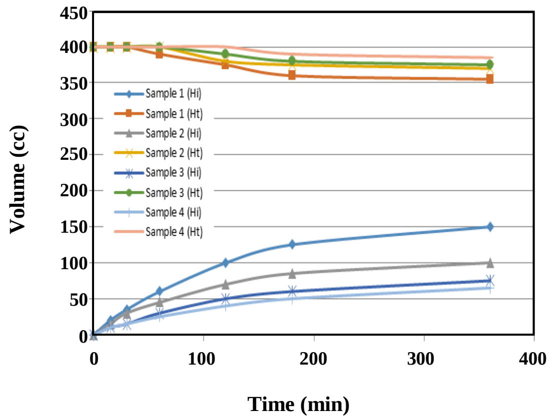

Fig. 2: XG concentration effect on the stability of aphron fluid (Surfactant SDS).

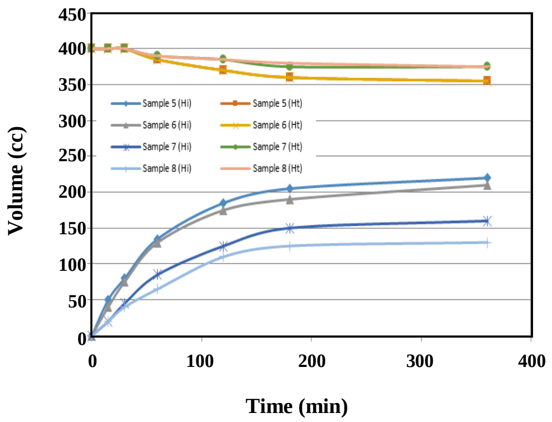

Fig. 3: Guar Gum concentration effect on the stability of aphron fluid (Surfactant CTAB).

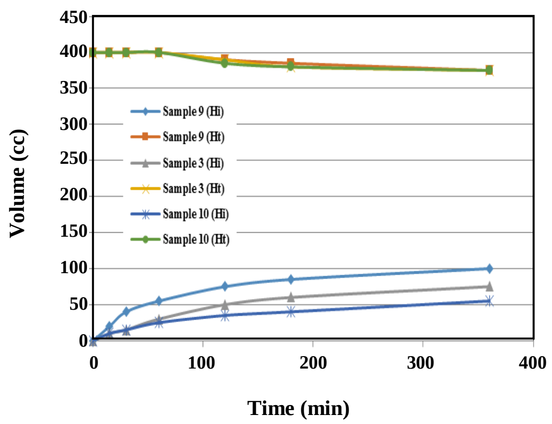

Fig. 4: SDS concentration effect on the stability of aphron fluid (Polymer XG).

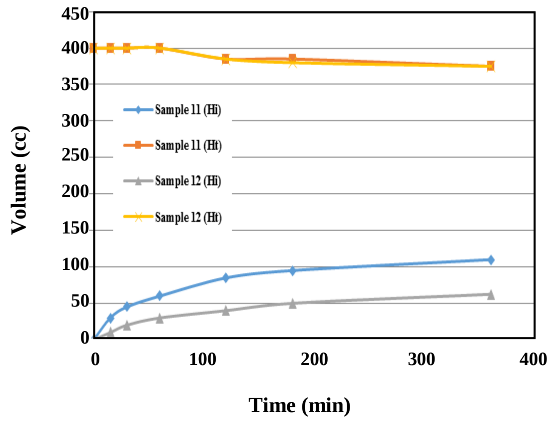

Fig. 5: CTAB concentration effect on the stability of aphron fluid (Polymer XG).

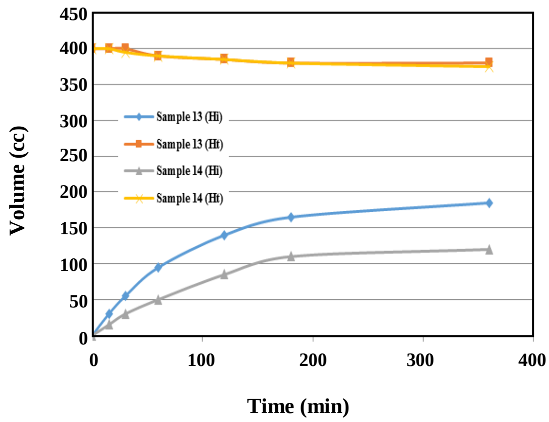

Fig. 6: SDS concentration effect on the stability of aphron fluid (Polymer Guar Gum).

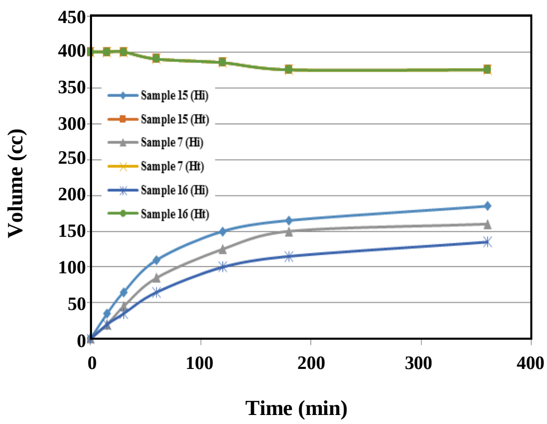

Fig. 7: CTAB concentration effect on the stability of aphron fluid (Polymer Guar Gum).

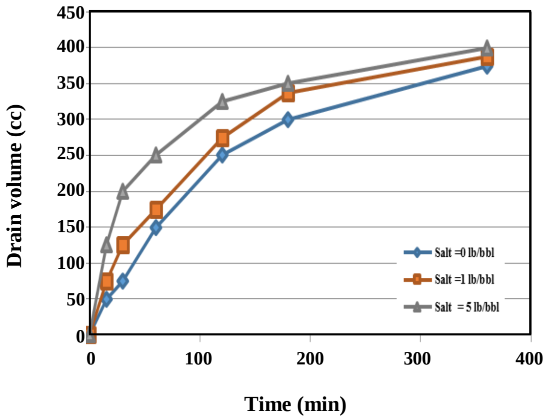

Fig. 8: Effect of $CaCl_2$ concentration on aphron stability.

dispersions. By comparing the samples of 1, 3, 5, and 7 it is concluded that XG polymer is more effective than Guar Gum. From the other point by comparing the samples of 1, 2, 3, and 4, it shows that for the sample of 1.0 lb/bbl XG, the fluid rapidly splits into two distinct phases. But after that by increasing the polymer concentration, the phase segregation slows down in a slower rate. This stability can be ascribed to at least two processes: increasing the effective viscosity of the solution from the presence of more polymer molecules, resulting in greater the aphron film thickness, thereby reducing the rate of film water to the bulk solution [10]; and also the higher solution viscosity retards the hydrodynamic outflow of liquid around the aphron bubbles driven by buoyancy forces.

Drainage curves for CGA dispersions with various surfactant concentrations are shown in Figs. 4 and 7. The rate of drainage, however, was not greatly influenced by the surfactant concentration. In another test, the effect of presence and concentration of a well-known contaminant namely $CaCl_2$ in the drilling fluid are investigated. Fig. 8 shows the effect of $CaCl_2$ on the aphron stability (Sample No. 3). Two different concentrations of 1.0 lb/bbl and 5.0 lb/bbl were chosen. As it is apparent, the fluid stability decreases by increasing the salt concentration. After a about 120 min after the start of test, more than 50 mL of the fluid has separated and accumulated at the bottom of the test cylinder. Experimental results of static drainage tests showed that after certain period of time, CGAs tend to separate, forming a two layers system, where dry CGAs stay on top and drained polymer solution stay on bottom. However, dissimilar to completion fluid, drilling fluids is always in motion during drilling operation. In the field, drilling fluid is circulated down through the drill pipe. Then, it exits through nozzles of bit and return to the surface. As fluid separation will be prevented by circulation and stirring, the problem of instability and phase separation is not a critical issue.

CONCLUSIONS

The major applications of rheological properties for evaluating drilling fluid behavior are in solving problems of hole cleaning and hole erosion, suspension of cuttings, hydraulic calculations, and drilling fluid treatment. The objective of the present study was to describe some characteristics of colloidal gas aphron based drilling fluids in general with specific emphasis on filtration loss and rheological properties and stability of them. To accomplish this end, using a rotational viscometer, the rheological parameters based on theory of Bingham plastic were measured with different concentrations of polymers and surfactants. Also, in this article the aphrons performance as filtrate –reducing elements was tested thorough a standard filter press. As static drainage test was also applied to examine the stability of prepared samples.

In the first part of this study, it was observed that with increasing surfactant concentration, apparent viscosity, plastic viscosity and yield strength increased. Increase of abovementioned rheological parameters is due to the increase of colloidal forces operating between aphron microbubbles with increase of surfactant concentration. This is desirable for drilling fluid as it sets to a gel, which is sufficient to suspend the cuttings when circulation is stopped and also breaks up quickly to a thin fluid when it is agitated by resumption of drilling.

After aphronization of the base fluids, API filtration loss reduced. This can be attributed to the majority of air microbubbles which are available to create an external bridge in front of pore structure by their accumulation. API filtration losses decreased by about 50% or even more as the polymer concentration increased from 1.0 lb/bbl to 2.5 lb/bbl. System with the higher surfactant concentration found more effective sealing ability because it has higher concentration of microbubbles with greater average diameter of aphrons which significantly controls fluid seepage into the formation.

The concentration of XG in the formulation greatly influences the stability of CGA dispersions. Increasing the XG concentration decreased the rate of phase separation. Based on these test it was found that XG polymer is morew efficient in keeping the fluid uniform than the Guar Gum. At the end, effect of fluid contamination by $CaCl_2$ was investigated and found that the presence and concentration of salt have a direct effect on the fluids static behavior in terms of stability.

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