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Applications of Novel Aphron Drilling Fluids

Frederick B. Growcock, Gerard A. Simon, Jose Guzman and Ben Paiuk, M-I SWACO

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Abstract

A few years ago, a novel drilling fluid containing specially designed microbubbles, or "aphrons," was introduced. This aphron drilling fluid has now been used to drill successfully through numerous formations which previously had experienced unacceptably high losses and differential sticking. Low fluid invasion results from (a) a base fluid that is highly shear-thinning and possesses low thixotropy, and (b) microbubbles that can seal pores and microfractures.

Recent developments have led to aphron drilling fluid systems with enhanced viscosity profiles, improved filtration control and reduced lost circulation potential. In one system, special clays decrease ECDs and provide structure at low shear rates that prevents drilled solids from compacting, thus facilitating their removal from the wellbore. A polymer/surfactant package has been introduced that works in all of the systems to increase the longevity and resistance of the bubbles to pressurization, rendering aphron-based systems even more effective for sealing problematic loss zones.

The authors discuss the design and properties of aphron drilling fluids, with particular emphasis on recent innovations and how these systems provide superior performance in drilling operations with a high risk of lost circulation.

Introduction

Aphron fluids have been used successfully in numerous applications worldwide to drill microfractured environments, high-permeability formations, and depleted reservoirs in mature oil and gas fields.[1-3] They have also proven to be a successful, cost-effective substitute to underbalanced drilling.

These microbubble fluids have two distinctive features that lead to minimal fluid invasion and minimal damage to the formation. First, the base fluid is very highly shear-thinning and possesses a low-shear-rate viscosity much higher than conventional muds or reservoir drilling fluids. Furthermore, low thixotropy, as evidenced by non-progressive gel strengths, enables the fluid to generate high viscosity very quickly upon entering a loss zone. Second, the microbubbles (aphrons) are sufficiently sturdy, yet flexible, to serve as an effective, minimally damaging bridging material. Furthermore, aphrons can be incorporated into the bulk fluid with conventional mud mixing equipment. This reduces costs and safety concerns associated with high-pressure hoses and compressors commonly used in air or foam drilling.[4]

In this paper, we describe recent innovations and field applications of aphron drilling fluids.

Aphron Structure and Composition

Drilling fluid aphrons are composed of two fundamental elements:[5] (1) a core of air, and (2) an outer surfactant-containing shell composed of a hydrophobic cover to protect against coalescence with nearby aphrons. A conventional bubble is stabilized by a surfactant monolayer (**Fig. 1**) whereas an aphron achieves its enhanced stabilization with a much stronger and impermeable shell consisting of a trilayer of surfactants (**Fig. 2**).[5] The innermost surfactant film is covered with a sheath of viscosified water and a surfactant double-layer that renders the aphron hydrophilic and thus compatible with the continuous aqueous mud phase. When sufficient shear or compression is applied to an aphron, the outermost surfactant layer is stripped off and yields a structure that is hydrophobic.[3,5]

Aphrons behave as a bridging material; consequently, proper sizing and concentration are critical to their effectiveness as sealants of permeable and fractured formations. In the field, aphrons are generated in the drilling fluid through the use of conventional mud-mixing equipment and specialized aphron-generating surfactants. Aphrons are thought to be "polished" at the bit jets to achieve a more uniform size distribution. The system is generally designed to incorporate 12 – 15% v/v air at surface conditions and measured by fluid density, though this can be adjusted according to the needs of the individual operator.

Various techniques are utilized to characterize aphrons: (1) Acoustic Bubble Spectrometry, a technique which enables analysis of opaque fluids; (2) Sight Flow Pressurization, which allows for visualization of the aphrons under varying pressures; (3) Triaxial Loading Core Leak-Off, which enables aphron strength testing, sealing capability, and formation damage potential under varying pressures and temperatures; and (4) Particle-Size-Distribution Analysis. Under ambient conditions, aphrons in the field range in size from 15-100 µm in diameter.[6-8]

Stabilization of aphrons is achieved through control of the size, collision rate and the mechanical properties of the bubbles. The size is a function of the shear energy put into the system, and surfactant type and concentration. The collision rate is inversely proportional to the viscosity of the medium. Increasing bulk viscosity of the aphron drilling fluid decreases the collision rate. Thus, a fluid with a very high low-shear-rate viscosity reduces fluid leak-off to the formation and damage potential (particularly if it exhibits low thixotropy), but it also minimizes bubble interaction in the loss zone until the bubbles reach a pore throat or a fracture tip and bridge the opening.[3]

Of the mechanical properties important for aphron stabilization, low permeability is among the most critical. Permeability is the tendency for water and air to escape from the aphron shell and core of the bubble, respectively. This property is thought to be a strong function of the shell thickness[5] and interfacial viscosity.[9] The thickness and viscosity of the aphron shell are controlled by the unique chemistry of the components incorporated in the shell, The propensity for water from the bubble shell to diffuse into the bulk liquid (Marangoni effect[5,9,10]) causes thinning of the shell and ultimately rupture of the bubble. A thicker and more viscous shell will not thin as readily. Similarly, when pressurized, the rate at which air diffuses out of a bubble decreases with increasing shell thickness and viscosity. Diffusion of air from conventional bubbles into the bulk fluid occurs in only a fraction of a second.[11] Visualization experiments indicate that aphrons, on the other hand, can survive up to at least 1500 psia for extended time intervals. Conversely, in a pressurized aphron drilling fluid supersaturated with (solubilized) air, PVT experiments suggest there is a significant lag time in generation of aphrons from the solubilized air during depressurization.[6]

Aphron Drilling Fluid Properties

Tables 1a and 1b illustrate the formulations of typical polymer and clay-based aphron drilling fluids. Each fluid consists of viscosifiers, pH control additives, aphron generators and stabilizers, and fluid-loss-control additives. The main difference in the two systems is the type of viscosifier.

Standard API properties (**Table 2**) for each system were acquired in the laboratory, along with LSRV (Brookfield viscometer, L3 spindle, 0.06 sec^{-1}) and "Half-Life" (3 hr) at 70° F after hot-rolling at 150° F for 16 hr. The Half-Life calculation procedure is given in **Appendix A**. There is little overall difference in the properties of the polymer-based and clay-based aphron systems. Although the overall rheological profile of the clay-based aphron system is slightly lower, the fluid loss is twice the value of the polymer-based aphron system.

Ability of Aphrons to Reduce Losses

The aphron shell is engineered to be hydrophobic, allowing aphrons to agglomerate, yet resist coalescence. As the aphron drilling fluid enters a formation (**Fig. 3**), the individual aphrons are forced together into a large, network not unlike that of a true foam (>70% vol air), thereby forming an internal bridge.

Laboratory Leak-off Tests using a Triaxial Loading Core Leak-Off Tester (**Fig. 4**) were run according to the procedure outlined in **Appendix B**. Results indicate that both polymer-based and clay-based aphron drilling fluids can effectively seal cores of even very high permeability (at least as high as 80 darcy). An example is given in **Table 3** for sealing of a 10-darcy core using a low wellbore pressure and no back pressure. In this example, the clay-based aphron fluid appears to provide even lower leak-off than the polymer-based fluid. Furthermore, the seal is significantly better with air, *i.e.* with aphrons, than without air.

Aphron Drilling Fluid Field Trial in Veracruz, Mexico

Recently, the latest version of a polymer-based aphron drilling fluid was run on the Copite-92 well, onshore about 50 km out of Veracruz, Mexico (**Fig. 5**). The interval drilled was a depleted fractured limestone. Rock fracture geometry on a core sample from that interval was determined by means of Scanning Electron Microscopy (**Fig. 6**) to assess whether aphrons would be capable of bridging the fractures. Most fractures observed were not active (sealed) and had an average aperture of about 10 μm. Larger fractures (with apertures of 70 to 100 μm) were also observed, but these were deemed to be permanently sealed.

Fluid losses in this field are quite common and generally very high, even when using light-weight direct emulsions. The casing program of Copite-92 (**Table 4**) indicates that the aphron-based system was employed to a TD of 9364 ft. This interval was drilled using the aphron drilling fluid with only minor losses reported.

The operator showed high satisfaction with the performance of the drilling fluid. Unfortunately, during the follow-up cementing job, significant fluid losses were observed, and no production data have been available since the well was completed. A second trial for the aphron drilling fluid is planned in the same field.

Summary

Both polymer-based and clay-based aphron drilling fluids are able to successfully control fluid losses to high-permeability and microfractured formations. It is believed that these fluids reduce whole mud losses via a combination of very high low-shear-rate viscosity and plugging by uniquely stabilized microbubbles. The chemistry of these bubbles – aphrons – enables them to survive under downhole conditions and to bridge loss zones, ultimately forming a minimally damaging internal filter cake.

Significant modifications to the chemistry of aphron drilling fluids have led to the development of an enhanced polymer-based aphron drilling fluid and a new clay-based aphron drilling fluid. The enhanced polymer-based aphron drilling fluid was successfully tested in an onshore field trial near Veracruz, Mexico.

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Nomenclature

BHT = *bottom hole temperature*
ECD = *equivalent circulation density*
PVT = *pressure volume temperature*
TVD = *total depth*

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SI Metric Conversion Factors

bbl	x 0.159	= m^3
cP	x 1.00	= mPa-s
°F	x (°F-32) X 5/9	= °C
ft	x 0.3048	= m
gal	x 0.00379	= m^3
in	x 0.0254	= m
lb	x 0.454	= kg
lb/bbl	x 2.853	= kg/m^3
lb/gal	x 119.8	= kg/m^3
lb/gal	x 0.120	= specific gravity (sg)
lbf/100 ft^2	x 0.478	= Pa
psia	x 6.895	= kPa

Appendix A – Half-Life of Entrained Air

The Half-Life method serves as a simple way to determine bubble stability of aphron-based drilling fluids. The calculation assumes that the rate of loss of undissolved air follows standard first order kinetics, as in the case of a true foam. Although aphrons are better characterized as dispersed bubbles rather than foams and their rate of decay is not strictly first order, experience indicates that the Half-Life is a fair trend indicator of bubble stability.

First determine the “initial” amount of undissolved air incorporated in the mud, or Air Quality, using the following expression:

$$\%\ Air_i = [(d_t - d_i)/d_t] \times 100 \qquad \text{(Eq. A1)}$$

where d_t is the theoretical density of the air-free mud and d_i is the initial density after the aphron generation step.

Determine the “final” amount of undissolved air incorporated in the mud after some arbitrary period of time, t_f, e.g. 3 hr, 24 hr:

$$\%\ Air_f = [(d_t - d_f)/d_t] \times 100 \qquad \text{(Eq. A2)}$$

The rate coefficient for loss of air from the mud, K_{Air}, is given by:

$$K_{Air} = t_f^{-1} \ln (\%\ Air_i/\%Air_f) = t_f^{-1} \ln (d_t - d_i)/(d_t - d_f) \qquad \text{(Eq. A3)}$$

where d_f is the “final” mud density after the desired waiting period. Note that the Half-Life for decay of the Air Quality, $\tau_{1/2}$, is simply equal to

$$\tau_{1/2} = \ln 2 / K_{Air} = 0.693/K_{Air} \qquad \text{(Eq. A4)}$$

or $$\tau_{1/2} = 0.693\ t_f \times \ln^{-1} (d_t - d_i)/(d_t - d_f) \text{ in hr} \qquad \text{(Eq. A5)}$$

Appendix B – Triaxial Loading Core Leak-Off Test Procedure

1. Saturate core with water.
2. Mount core in Leak-Off Tester and apply confining stress to at least 500 psig above system pressure.
3. Raise oven temperature to BHT for the formation core.
4. Apply back-pressure if so desired.
5. Raise system pressure via accumulator to desired pressure.
6. Open accumulator to allow for core injection.
7. Treat core for 30 min with aphron-based drilling fluid, monitoring effluent weight versus time.

Table 1a - Formulation of a Typical Polymer-Based Aphron Drilling Fluid System

Component	**Function**	**Concentration**
Fresh water/brine	Continuous phase	0.97 bbl
Soda ash	Hardness Buffer	3 lbm/bbl
Biopolymer blend	Viscosifier	5 lbm/bbl
Polymer blend	Filtration Control Agent and Thermal Stabilizer	5 lbm/bbl
Alkalinity Control Agent	pH control	0.5 lbm/bbl
Surfactant Blend	Aphron Generator	2 lbm/bbl
Biocide	Biocide	0.05 gal/bbl
Polymer/Surfactant Blend	Aphron Stabilizer	1 lbm/bbl
Polymer	Shale Stabilizer	1 lbm/bbl
Oligomer*	Defoamer	As Needed

*Optional component

Table 1b - Formulation of Typical Clay-Based Aphron Drilling Fluid System

Component	**Function**	**Concentration**
Fresh water/brine	Continuous phase	0.97 bbl
Soda ash	Hardness Buffer	0.25 lbm/bbl
Caustic Soda	Alkalinity Control Agent	1.5 lbm/bbl
Clay/Polymer Blend	Viscosifier	25 lbm/bbl
Polymer Blend	Filtration Control Agent and Thermal Stabilizer	2 lbm/bbl
Surfactant Blend	Aphron Generator	0.5 lbm/bbl
Biocide	Biocide	0.05 gal/bbl
Polymer/Surfactant Blend	Aphron Stabilizer	1 lbm/bbl
Polymer	Shale Stabilizer	0.2 lbm/bbl
Oligomer*	Defoamer	As Needed

*Optional component

Table 2. Standard Properties of Polymer-Based and Clay-Based Drilling Fluids

Formulation			
Additive	**Units**	**Polymer**	**Clay**
Sea Water*	mL/lab bbl	338	331
Soda Ash	g/lab bbl	3.0	0.3
Caustic Soda	g/lab bbl		1.5
Biopolymer Blend	g/lab bbl	5.0	
Polymer Blend	g/lab bbl	5.0	
Clay/Polymer Blend	g/lab bbl		25.0
Polymer Blend	g/lab bbl		2.0
Alkalinity Control Agent	g/lab bbl	2.0	
Aphron Generator	g/lab bbl	1.0	0.5
Shale Inhibitor	g/lab bbl	1.0	0.2
Aphron Enhancer	g/lab bbl	1.0	1.0
Std API Viscosity, 120 F			
600	°	94	84
300	°	78	63
200	°	70	53
100	°	60	42
6	°	39	23
3	°	36	22
PV	cP	16	21
YP	lbf/100 ft^2	62	42
Gel 10 sec	lbf/100 ft^2	39	30
Gel 10 min	lbf/100 ft^2	58	46
LSRV (0.06 sec^{-1}), 70F	cP	192,000	130,000
API Fluid Loss	mL/30 min	7	14
Half-Life	hr	152	108

Table 3. Triaxial Core Tester Net Leak-Off Data

$P_{confining}$ = 2500 psig, P_{inlet} = 100 psig, P_{outlet} = 0 psig, 10-Darcy Aloxite 2-in. length x 1½-in. diameter, 77°F

Aphron Drilling Fluid	**Leak-off, mL/30min**	
	No Air	**15% Air**
Polymer-Based	29	21
Clay-Based	22	10

Table 4. Casing Program for Copite 92 well in Veracruz, Mexico

Casing Diameter (in.)	**Measured Depth (m)**	**Mud System**	**MW (g/cm^3)**	**Bit Size (in)**
13⅜ Conductor	50	Bentonite	1.10	17½
9 ⅝ Surface	400	Polymer	1.23	12¼
7 Intermediate	2481	OBM	1.28	8½
5 Liner	2854	Aphron	1.12	6

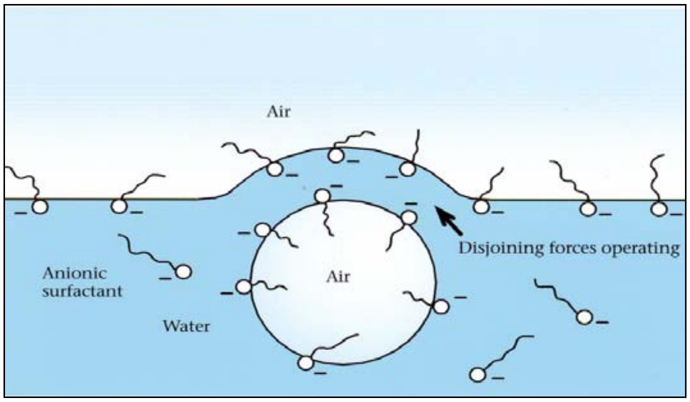

Fig. 1 - Schematic of Conventional Bubble

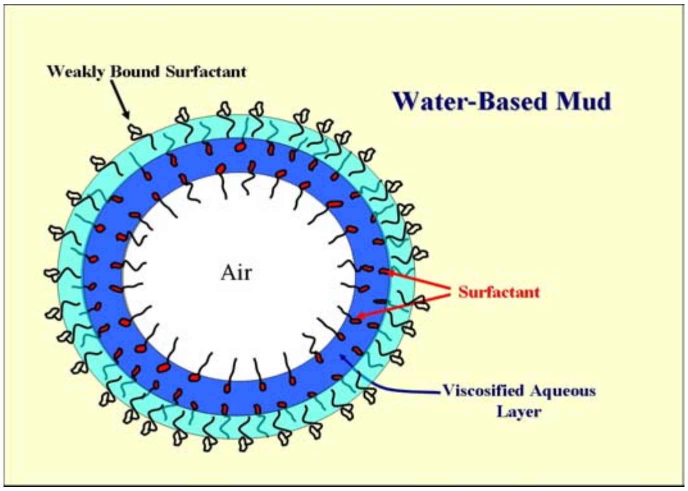

Fig. 2 - Schematic of an Aphron

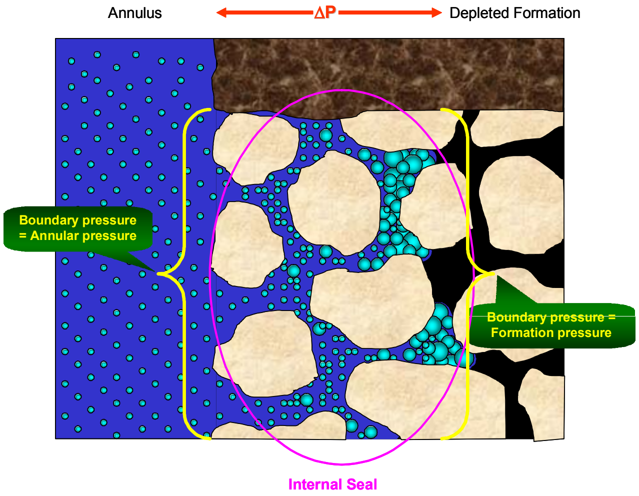

Fig. 3 - Formation Invasion by Aphron Drilling Fluid

Fig. 5 - Location of Copite-92 Well

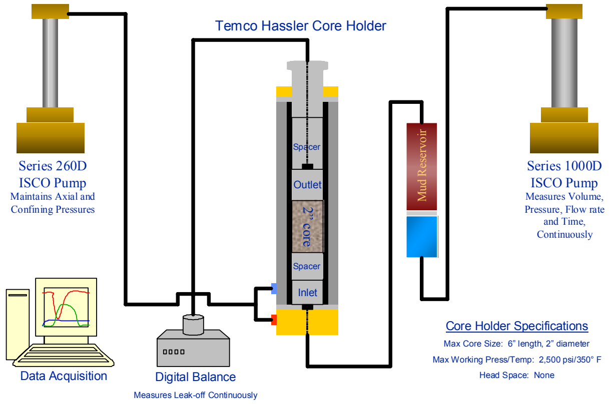

Fig. 4 - Triaxial Loading Core Leak-Off Tester

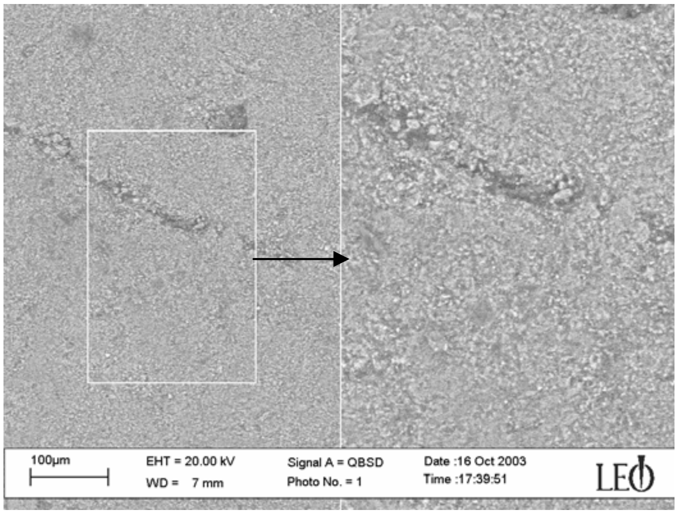

Fig. 6 - Typical Inactive Fracture on a Limestone Sample from Copite-18 Well