J Petrol Explor Prod Technol (2014) 4:337–342
DOI 10.1007/s13202-013-0094-6

ORIGINAL PAPER - EXPLORATION ENGINEERING

Recirculated aphron-based drilling fluids

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Received: 25 February 2013 / Accepted: 9 December 2013 / Published online: 17 December 2013

Abstract The aphron-based drilling fluids are designed to minimize formation damage by blocking the pores of the rock with micro-bubbles, which can later be easily removed when the well is open for production. Micro-bubbles behave like tough, yet flexible bridging materials, and form an internal seal in a pore-structure. Proper sizing of the micro-bubbles with respect to pore size distribution is essential for developing an aphron-based drilling fluid with effective sealing ability. The properties like rheology and compatibility with oils also need to be better understood. In this study, the size distribution of aphrons as well as the change in the aphron size with time was determined using a visual imaging technique. Formation fluid compatibility was conducted to evaluate the compatibility between the aphron-based drilling fluids with four oils. The effects of pressure and temperature on the rheological properties of aphron-based drilling fluids were also investigated, and the regression analysis method was used to establish the constitutive equations of tested liquids under various temperatures.

Keywords Aphrons · Size distribution · Rheological property · Regression analysis · Compatibility

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Introduction

Many oil and gas reservoirs have stepped into mature period, and become increasingly depleted. Due to their higher pore pressures, formations above and below these producing zones need to be stabilized by fluids with higher density. However, an exposure of a depleted zone to the required high-density fluid can cause a significant loss of the whole fluid and differential sticking. Furthermore, uncontrollable drilling fluid losses are at times unavoidable in the large fractures of these formations. So it is difficult to drill such zones economically and safely by means of conventional rig equipments. Underbalanced drilling may be an alternative, but the extra time and equipments can greatly increase the cost of the operation.

Recently, a new drilling fluid technology has been developed in an attempt to eliminate just these discussed problems. This novel technology is based on aphrons—uniquely structured micro-bubbles of air. The air used to generate aphrons is usually incorporated into the fluid with conventional fluid-mixing equipment at ambient pressure, thereby reducing costs and safety concerns associated with conventional air and foam drilling operations. Since the amount of air in the fluid is very low, normally 12–15 vol% at ambient temperature and atmospheric pressure (Berkin et al. 2005), the density of the fluid downhole is similar to that of the base fluid. The aphrons behave like solid, yet flexible bridging materials, and can adjust the shape automatically according to the size of fractures, cavern, or openings to control lost circulation with minimum formation damage. It has been successfully used in California, Lake Maracaibo, North Sea, China, and Albert (He 2010), and has been proven to be a cost-effective alternative to underbalanced drilling.

In this study, the size distribution of micro-bubbles,change in the size of micro-bubbles with time, and crude oil compatibility were evaluated. The effects of pressure and temperature on the rheological properties of the aphron-based drilling fluids were also investigated.

Aphron structure description

According to Sebba (1987), aphrons are bubbles approximately 10–150 microns in diameter. Unlike conventional foam bubbles, aphrons have the structure of "One core, two layer, and three membranes". The gas core of aphron is encapsulated by an aqueous protective shell. This tough, impermeable shell helps to prevent leakage of air from the core, and allows the aphrons to survive downhole pressures. In fact, the shell is surfactant tri-layer. The outer surfactant layer is thought to be hydrophilic, making the aphrons compatible with the surrounding water-based fluid, and produces an effective barrier against coalescence with adjacent aphrons. So, aphrons show little affinity for each other, as shown in Fig. 1. However, the aphrons can attract one another to form complex aggregates, which behave in the same manner as the individual aphron (Ivan et al. 2002).

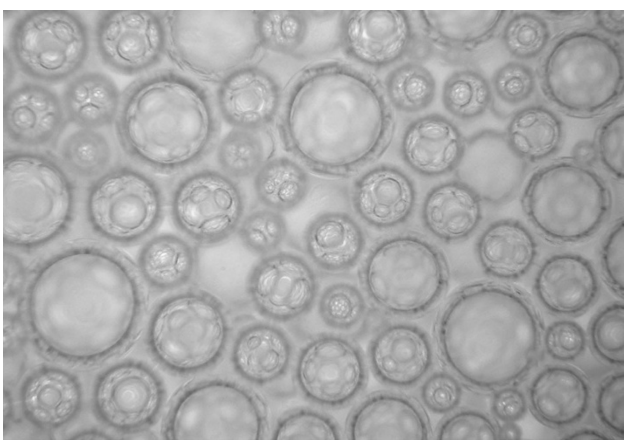

Fig. 1 Typical microscope picture of water-based aphrons (×40)

Table 1 Formulation of aphron-based drilling fluids

Component	Concentration (wt%)	Function
Water	100	Continuous phase
Bentonite	4	Gel builder
Soda ash	0.2	Hardness buffer
Caustic soda	0.1	pH control agent
Polymer1	0.4	Filtration control agent; viscosifier
Polymer2	0.4	Aphron stabilizer; viscosifier
Surfactant	0.2	Aphron generator

Table 2 Properties of water-based drilling fluids

Properties	Initial	HotRoll 16 h at 120 °C
Density (g/cm^3)	0.8	0.84
Funnel viscosity (s)	64	56
Apparent viscosity (cP)	41.5	37
Plastic viscosity (cP)	27	25
Yield point (Pa)	14.5	12
YP/PV	0.54	0.48
Gel strength 10 s/10 min (Pa)	4/9	5/11
API fluid loss (mL/30 min)	5.1	4.9
pH	9.7	9.7
Half-life (h)	>48	>48

System composition and basic properties

Table 1 displays the composition of typical aphron-based drilling fluids, consisting of appropriate pH control additives, viscosifiers, aphron stabilizer, fluid loss control additives, and aphron generator that create and stabilize the micro-bubbles in the system. The basic mud properties like density, pH, standard API rheology, and half-life were measured at room temperature prior to and after hot rolling at 120 °C for 16 h. The results are given in Table 2.

The most dominant characteristics of aphron drilling fluids are the presence of aphrons and their rheology (Kinchen et al. 2001). The surfactant in the fluid is incorporated to achieve the desired concentration of aphrons, and produce the surface tension to contain the aphrons as they are formed. Also, the surfactant can build the multiple-layer shell and create interfacial tension to bind the aphrons into a network capable of creating downhole bridging.

To successfully complete the operation, the aphrons must be stabilized in the drilling fluids. This has been achieved by high yield stress, shear thinning (HYSST) polymer. This type of polymer is regarded as viscosifier as well as stabilizer. The use of HYSST polymer coupled with filtration control agent will help control the rheological properties (i.e., shear viscosity, low shear rate viscosity), and stabilize the aphrons by preventing the growth of bubbles with time.

Aphrons diameter

Measurement of aphrons size distribution

The diameter of the aphron bubble is an essential factor for determining the aphronized fluids seepage into the formation while drilling. Sizing of the bubbles should be in

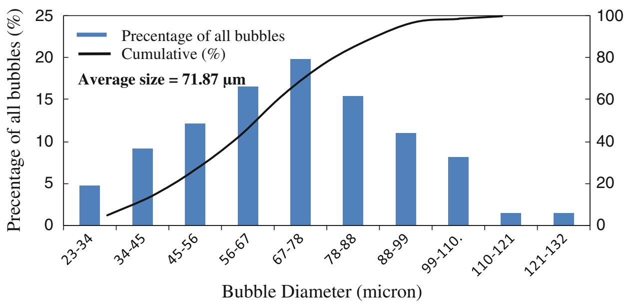

Fig. 2 Size distribution of micro-bubbles

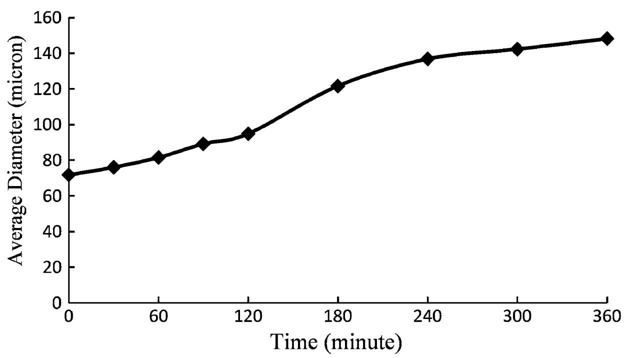

Fig. 3 Effect of time on the average diameter of micro-bubbles at ambient temperature and atmospheric pressure

accordance with the pore size distribution of the formation rock (Vicker et al. 2006). So, it is of great importance to measure the size distribution of micro-bubbles rather than just look at the average bubble size. In this paper, the size of aphrons was determined using a visual imaging technique reported by Nareh et al. (2012). The result of bubble size distribution is shown in Fig. 2. It is clear that the aphron-based drilling fluids show a wide size range. Most of the bubbles lie between 20 and 130 µm with the average bubble size is 71.87 µm.

Measurement of aphrons size change with time

The stability of micro-bubbles with time is also an important factor for determining the ability of the aphrons to block rock pores. Figure 3 shows the curve of average bubble size as a function of time at ambient temperature and atmospheric pressure. It can be clearly seen that the aphrons grow bigger at the first 3 h, and then they grow at a relatively smaller pace, and ultimately reach a stable value of about 150 µm after 6 h. These results are in good agreement with those reported by Nareh et al. (2012) and Bjorndalen and Kuru (2008).

Figure 4 shows two pictures taken on a same scale for analysis of bubble diameter with time. One is the freshly prepared aphron-based drilling fluids as seen in Fig. 4a, and the other is fluids after 48 h have passed as shown in

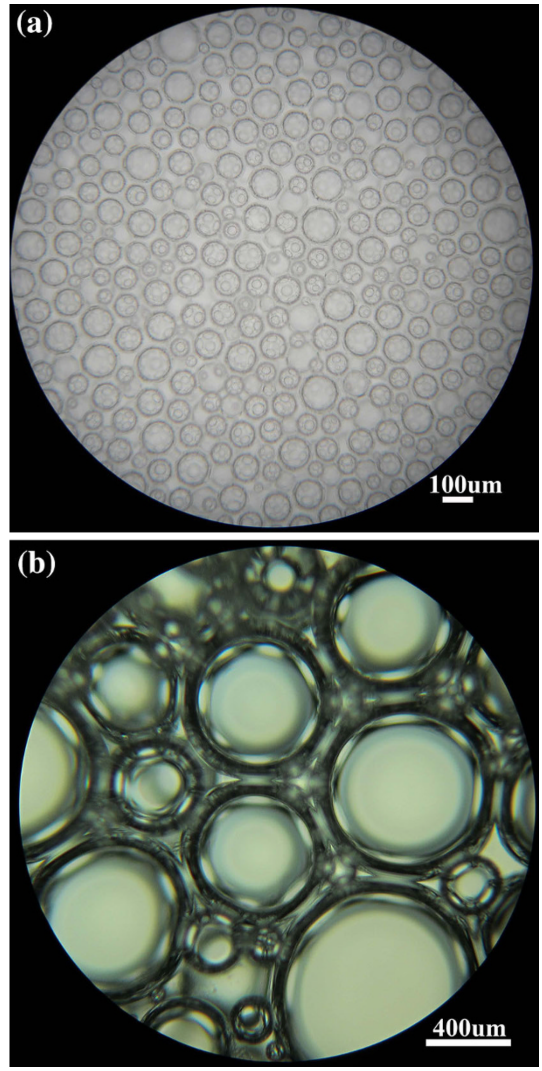

Fig. 4 **a** Microforms of freshly prepared micro-bubbles. **b** Microforms of micro-bubbles standing for 48 h

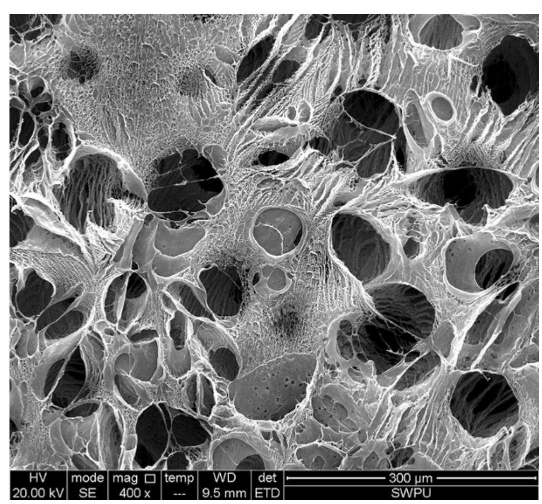

Fig. 5 E-SEM photo of aphron-based drilling fluids after completely deforming

Fig. 4b. Evidently, the aphrons grow in size with time accompanied by simultaneous breaking up of bubbles which was observed with the microscope.

Environmental SEM photos were also taken of this sample when it has completely deformed, an example of which is shown in Fig. 5. It can be clearly seen that the polymer/surfactant residue left seems to form a typically screen structure, just like the structure of zeolite.

Formation fluid compatibility

The evaluation of formation fluid compatibility was carried out between aphron-based drilling fluids and produced fluids to see whether any obstacle might exist for producing fluids through an aphrons invasion zone. Different oils were tested at room temperature, including diesel oil and three crude oils: SZ36-1 (SuiZhong), JZ-93 (JinZhou), and LD10-1 (LvDa). Three volume ratios of oil to aphron-based drilling fluids were tested: 25/75, 50/50, and 90/10. More precisely, the tested oil/drilling fluid proportions were blended at 300 rpm for 5 min, and then immediately placed in the graduated cylinders, so the rate of separation of the two phases could be measured (Quintero and Jones 2003). To determine the wetting properties of the oil/mud mixtures, a few drops of each mixture were dropped into a glass beaker filled with water. If the mixture clung together, it was deemed to be oil-wetting; if it dispersed, it was deemed to be water-wetting (Growcock 2005).

For the 25/75 mixtures, the diesel oil was the only one of the four tested oils which separated rapidly from the drilling fluids. In other cases, water-wetting emulsions were formed which did not break within 2 h. The mixtures were cream-like and contained large globules. Of all the tested oils, diesel was the only one with a relatively low viscosity, which may lead to the rapid phase separation.

As to the 50/50 mixtures, the diesel oil, as expected, separated rapidly from the drilling fluids, and the crude oil from SZ36-1, which is the most viscous of the four tested oils, separated completely from the drilling fluids within about 2 h. Other two oils attained complete separation within 1 h with a high separation rate in the first few minutes, as depicted in Fig. 6. The separation occurred despite of the high viscosity of the two phases, which suggests that emulsion blockage in reservoir pore is not probable.

As to the 90/10 mixtures, except for the crude oil from SZ36-1, which did not separate from the drilling fluids until 30 min have passed, all other oils separated almost immediately. One possible explanation is that the fluids did not contain sufficient surfactants to emulsify the mixtures which have large amounts of oil. Furthermore, it is worth noting that the emulsions converted from water-wetting to oil-wetting when the ratio of the oil grew from 50 to 90 %.

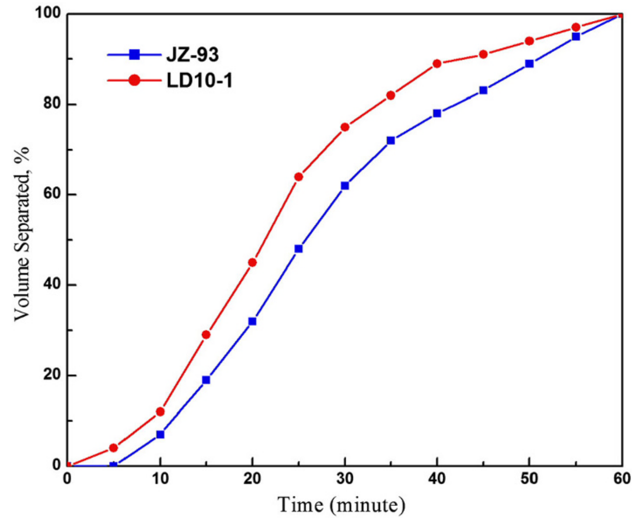

Fig. 6 Compatibility of 50 % crude oils/50 % aphron-based drilling fluids

It seems clear from the analysis above that the observed emulsification is mainly dominated by the viscosity of the oils and the surfactant in the drilling fluids. It also seems clear that large amounts of crude oils, generally as much as 25–50 vol% can be mixed with aphron-based drilling fluids, and still be water-wetting.

Rheological properties at HTHP

Aphron-based drilling fluids are complicated non-Newtonian fluids, and the Power Law model has been widely used to describe the rheological model of aphron-based drilling fluids at ambient temperature and atmospheric pressure (Nareh et al. 2012; Wang et al. 2007). However, since gas is easily influenced by the pressure and temperature than liquid, the pressure and temperature have much more effects on the rheological properties of aphron-based drilling fluids than on those of conventional water-based drilling fluids because of the air incorporated in aphrons. Thus, it is necessary to discuss the effects of pressure and temperature on the rheological properties of aphron-based drilling fluids.

The rheology measurements at HTHP were carried out with a 7400 HTHP Rheometer manufactured by Chandler, America. The variation of shear stress with shear rate was recorded at 0.1, 5.0, 10, 15, 20, and 25 MPa, and the shear stress versus shear rate behavior was also analyzed at 20, 60, 80, 100, 120, and 150 °C.

Effects of pressure on the rheological properties

As can be clearly seen in Fig. 7a, increasing pressure has little effect on the rheological properties of aphron-based drilling fluids. This is mainly attributed to the relatively smaller compressibility of liquid as well as the tough protective shell that wraps up outside the gas core. It is reported that the aphrons can survive exposure to elevated pressures much better than conventional bubbles, and can survive compression to at least 27.7 MPa. Also, the volume of aphron can recover nearly 90 % during depressurization (Berkin et al. 2005; Ivan et al. 2002; Wang et al. 2007; White et al. 2003; Growcock et al. 2006).

An aphron is much more than a "gas bubble". The viscosified water lamella, in tandem with the surfactant layers creates an "energized environment". First, when an aphron is generated inside a liquid, a new surface must be created, which increases in area in proportion with the growth of the bubble. This expansion must be balanced by an increase in the pressure within the bubble, thus explaining why the aphron is associated with an "energized environment" or "pre-compressed structure" (Međimurec and Pašić 2009).

Effects of temperature on the rheological properties

The effects of temperature on the rheological properties of aphron-based drilling fluids are a little more than those of pressure. As displayed in Fig. 7b, the shear stress of aphron-based drilling fluid shows a decrease trend with the elevated temperature. However, the range of variation is not so remarkable, especially at higher temperature. So the aphron-based drilling fluids seem to exhibit stability at high temperature. What is more, no obvious thickening and thinning were observed with the change of temperature.

Linear regression was conducted for rheological data of aphron-based drilling fluids under different temperatures using regression analysis method, and the constitutive equations of tested liquids were obtained, as shown in Table 3. It seems clearly that the rheological model of aphron-based drilling fluids at high temperature can still be best described by Power Law model with all the $R > 0.99$.

Low shear rate viscosity (LSRV)

LSRV is of great importance in controlling the invasion of aphron-based drilling fluids into formations. The LSRV of aphron-based drilling fluids is considerably higher than that of conventional reservoir drilling fluids and should always be maintained at more than 50,000 cP (Growcock et al. 2006). As the fluid slows due to radial flow and bridging action of the aphrons, the shear rate decreases and thus viscosity rises. This process will continue until the fluids stop. Stability of the LSRV properties is extremely crucial to maintain invasion control, a clean wellbore, and aphron stability (Brookey 1998). If the LSRV drops dramatically, it is highly recommended that drilling should be suspended until the rheological properties of drilling fluids are recovered.

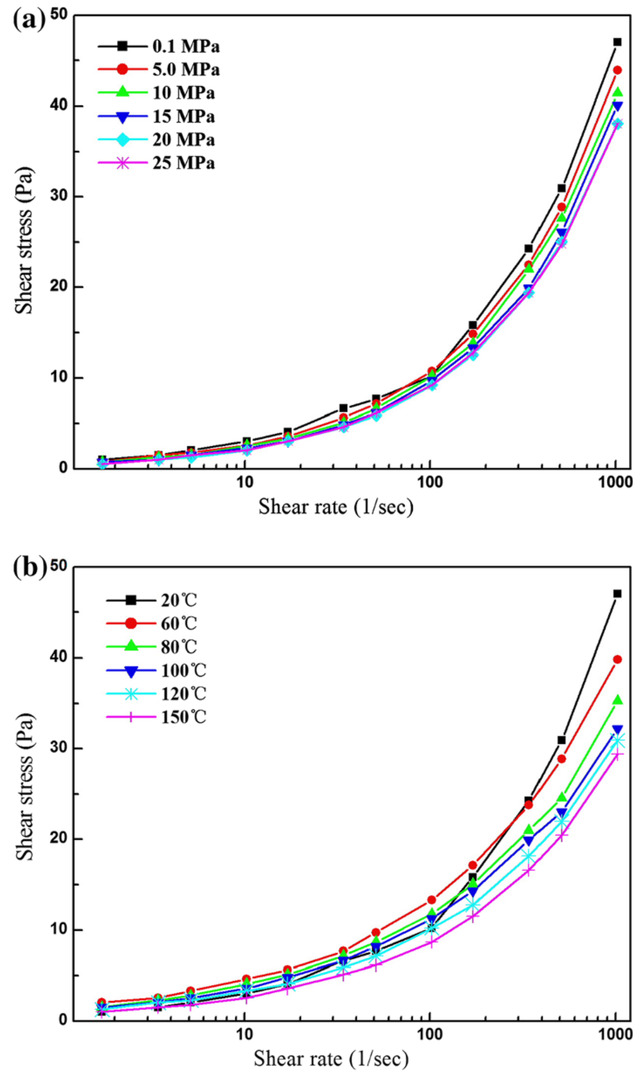

Fig. 7 **a** Effect of pressure on the rheological properties of aphron-based drilling fluids. **b** Effect of temperature on the rheological properties of aphron-based drilling fluids

Table 3 Fitting equations of Power Law model for aphron-based drilling fluids under various temperatures

T (°C)	Constitutive equations	R^2
20	$\tau = 0.7568\gamma^{0.5924}$	0.9983
60	$\tau = 1.5118\gamma^{0.4713}$	0.9992
80	$\tau = 1.2782\gamma^{0.4802}$	0.9989
100	$\tau = 1.1847\gamma^{0.4817}$	0.9991
120	$\tau = 1.0444\gamma^{0.4894}$	0.9991
150	$\tau = 0.7826\gamma^{0.5236}$	0.9996

The LSRV of the aphron-based drilling fluids was measured between 0.3 and 60 rpm using a Brookfield viscometer. The results obtained, as shown in Table 4, indicate that the fluid is highly shear thinning, and exhibits an extraordinarily high LSRV with viscosities approaching

Table 4 Low shear rate viscosity measured with a Brookfield viscometer

rpm	60	30	12	6	3	1.5	0.6	0.3
Viscosity (cP)	9,896	7,491	11,880	22,855	50,600	92,474	1,67,807	1,96,575

nearly 2,00,000 cP at the lowest shear rate. This high rheology may be caused by the interactions between the long chain polymer and the surfactant micelles (Quintero and Jones 2003).

Conclusions

The following conclusions can be offered based on the results obtained from this study:

1. The aphron-based drilling fluids show a wide size range. Most of the bubbles lie between 20 and 130 μm with the average bubble size is 71.87 μm.
2. The aphrons grow bigger in size with time, and the polymer/surfactant residue left after completely deforming seems to form a typically screen structure, just like the structure of zeolite.
3. Emulsification is mainly dominated by the viscosity of the oils and the surfactant in the drilling fluids. Large amounts of crude oils, generally as much as 25–50 vol% can be blended with aphron-based drilling fluids, and still be water-wetting.
4. Elevated pressure has little effect on the rheological properties of aphron-based drilling fluids.
5. The effects of temperature on the rheological properties of aphron-based drilling fluids are a little more than those of pressure. But the aphron-based drilling fluids seem to exhibit stability at high temperature.
6. The constitutive equations of tested liquids at various temperatures were obtained using regression analysis method, and the aphron-based drilling fluids can still be perfectly described by Power Law model at elevated temperature.

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