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APHRON-BASED DRILLING FLUIDS: SOLUTION FOR LOW PRESSURE RESERVOIRS

ISPLAKE NA BAZI AFRONA: RJEŠENJE ZA LEŽIŠTA S MALIM TLAKOM

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Ključne riječi: afroni, gubitak fluida, premošćenje, bušenje, opremanje, održavanje, iscrpljena ležišta

Abstract

Drilling wells throughout depleted or low pressure reservoirs requires low density drilling fluids, often with density less than water. Methods to reduce the density of drilling fluids have included mixing-in air or nitrogen. However, problems with these approaches include instability of gas bubbles (bubbles collapse or expand) and increased costs. Recently, the use of micro bubbles named aphrons in drilling, completion and workover fluids has proven success in solving many problems related to low pressure reservoirs such as fluid loss control, formation damage, stabilization of multipressure sequences with one fluid and possible differential sticking. Aphrons represent bubble with uniquely structure stabilized with surfactant. Against conventional micro bubbles, aphrons are more stable in downhole conditions and they are generated using standard mixing equipment. Owing to their properties and overpressure in wellbore aphrons penetrate into low pressure layers and set up inner bridging. Depleted wells which are very expensive to drill underbalanced or with other remediation techniques can now be drilled overbalanced. This paper presents description of aphron structure and stability, aphron bridging mechanism, aphron-based fluid composition and properties, and field experiences in applying aphron-based fluids.

Sažetak

Izrada kanala bušotine kroz iscrpljena ležišta ili ležišta sa smanjenim slojnim tlakom zahtijeva primjenu isplake male gustoće, često manje i od gustoće vode. Smanjenje gustoće isplake obično se postiže dodavanjem zraka ili dušika u isplaku. Nedostatak ovog pristupa smanjenju gustoće isplake očituje se u nestabilnosti mjehurića plina (sažimanje i ekspandiranje mjehurića) i povećanju troškova. U posljednje vrijeme, primjenom mikromjehurića nazvanih "afroni" u fluidima koji se koriste tijekom izrade, opremanja i održavanja bušotina, uspješno su rješeni mnogi problemi koji se odnose na ležišta s malim slojnim tlakom kao što su: gubljenje isplake, oštećenje formacije, stabilizacija intervala različitog slojnog tlaka i eventualni diferencijalni prihvat alatki. Afroni su mjehurići jedinstvene strukture koju stabiliziraju surfaktanti. U odnosu na standardne mjehuriće zraka afroni su stabilniji u uvjetima koji vladaju u bušotini, a za njihovo stvaranje koristi se standardna oprema za pripremu isplake. Zbog njihovih svojstava i većeg tlaka u kanalu bušotine nego u sloju, afroni ulaze u sloj te stvaraju unutrašnje premoštenje pornog prostora. Zahvaljujući tome, izrada kanala bušotine kroz iscrpljena ležišta može se odvijati u uvjetima nadtlaka što bitno smanjuje cijenu izrade bušotine i isključuje primjenu popravnih zahvata u kanalu bušotine. U članku se opisuje struktura i stabilnost afrona, mehanizam čepljenja pora afronima, sastav i svojstva fluida na bazi afrona, te navode primjeri iz prakse u kojima su opisana iskustva u korištenju ovih fluida.

Introduction

Conventional drilling fluids used when drilling the depleted or low pressure reservoirs very often generate the loss circulation and differential sticking problems. Using aerated drilling fluids or drilling underbalanced requires the extra equipment and special protection measures. Additionally, using these techniques for providing the hydrostatic pressure necessary to safely stabilize normally or high pressured formation above the low pressure reservoir, may be impossible or unsuccessful.

To solve loss circulation, borehole stability and differential sticking problems in low pressure reservoirs a specialized drilling fluid has been developed. This fluid, known as aphron-based drilling fluid, is highly shear-thinning and exhibits an extraordinarily high low-shear-rate viscosity (LSRV) with low thixotropy (flat gels) (Belkin et al., 2005.). It does not contain any conventional bridging agent for sealing the loss zone. The aphron-based drilling fluid combines certain surfactants to create aphrons or micro-bubbles. These aphrons are encapsulated in bulk fluid and have advantages regarding conventional air bubbles in aerated mud system. The air is purposely incorporated into the bulk fluid, but at a very low concentration. The aphrons are generated using conventional mud-mixing equipment, which entrains air up to level dictated by the concentration of aphron-generating surfactants, without requirements for any additional equipment such as those utilized in underbalanced air or foam drilling (White et al., 2003.). The surfactants in the fluid convert the entrained air into aphrons or highly stabilized bubbles. The aphrons are stable at downhole conditions, set up inner bridging in low pressure formations, prevent uncontrollable fluid loss, and prevent formation damage.

An aphron was found by Sebba (1987.). According to Sebba aphron is a soppy shell absorbing some surfactants staying in bulk water. Brookey (1998.) was the first one who introduced aphron (energized air bubble) into petroleum drilling industry and renamed aphrons as “micro-bubbles”. He described the first application of the aphron system in West Texas where a horizontal re-entry well was drilled through fractured dolomite in the Fusselman field. Up to now, aphron-based drilling fluid (also known as water-based micro-bubble drilling fluid -WMDF) has been used in drilling thousands of depleted reservoirs without any loss circulation problem (Brookey, 1998.; Ivan et al., 2001.; Kinchen et al., 2001.; Ramirez et al., 2002.; Schaneman et al., 2003.; Rea et al., 2003.; White et al., 2003.; Growcock et al., 2006. and 2007.; MacPhail et al., 2008.).

The Structure and Stability of Aphrons

The aphron is composed of a core of air (gas) that is stabilized by a polymer/surfactant shell. Figure 1 shows a conventional surfactant-stabilized bubble. It is simply a sphere of air separated from its aqueous surroundings by a thin film of surfactant (Sebba, 1987.; White et al., 2003.). The hydrophobic tail of the surfactant is oriented towards the gaseous core, while the hydrophilic head is oriented towards the bulk water. Thus, a conventional bubble has a water-wet or hydrophilic outer boundary.

In contrast to a conventional air bubble, which is stabilized by a surfactant monolayer, an aphron has more complex structure (White et al. 2003.; Ivan et al., 2001. and 2002.; Growcock et al., 2004[a]. and 2006.). The air core of an aphron is enveloped by a much more stable surfactant tri-layer (Figure 2). This tri-layer consists of (Belkin et al., 2005.):

- an inner surfactant film enveloped by a viscous water shell and
- an outer bi-layer of surfactants.

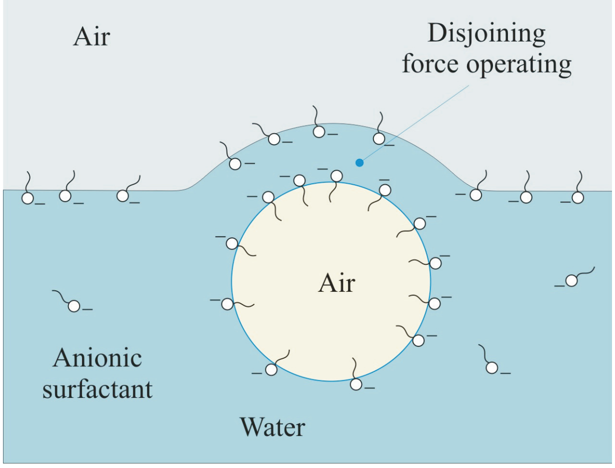

Figure 1 Structure of a conventional surfactant-stabilized bubble
Slika 1. *Struktura konvencionalnog mjehurića stabiliziranog sa surfaktantom*

The inner layer contains surfactants whose hydrophobic tails point into the air core and whose hydrophilic heads reside within the viscous water shell.

The outer surfactant layer is hydrophilic, making the aphron structure compatible with the surrounding water-based fluid. It provides rigidity and low permeability to the aphron structure.

The encapsulating shell (high-viscosity bi-layer) protects the aphrons, helps to prevent leakage of air from the core and allows the aphrons to survive downhole pressures.

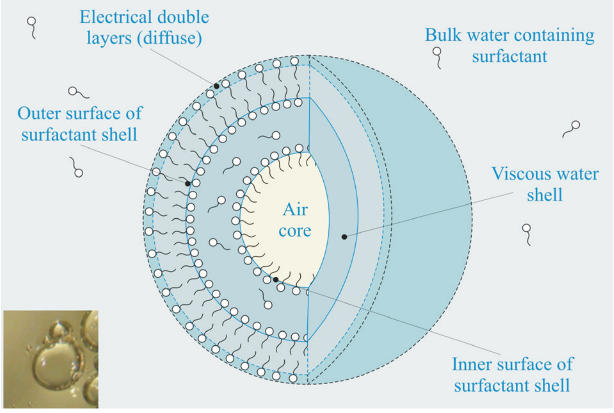

Figure 2 Structure of water-based aphron
Slika 2 *Struktura afrona u fluidu na bazi vode*

The structure of oil-based aphrons is thought to be similar to the structure of water-based aphrons (Figure 3). Viscosified aqueous or polar layer surrounds the inner surfactant film, and this is kept in place by an outer monolayer of surfactants.

The typical aphron size ranges from 10 µm to 100 µm in diameter, and they can survive recirculation through mud cleaning system. Most aphrons will not be removed even by fine screen shale shakers or flow line cleaners, and since they have little mass, they are retained even in hydrocyclones or high-speed centrifuges. Aphrons do not interfere with downhole tools such as MWD or mud motors making them ideal for directional and horizontal applications. Because of little amount of air incorporated in the base fluid (only 15% v/v at ambient temperature and atmospheric pressure) density of aphron based fluid is similar to density of the base fluid. High values of low-shear-rate viscosity (LSRV) help set up bridging and sealing formation (Brookly 1998.; Ramirez et al. 2002.).

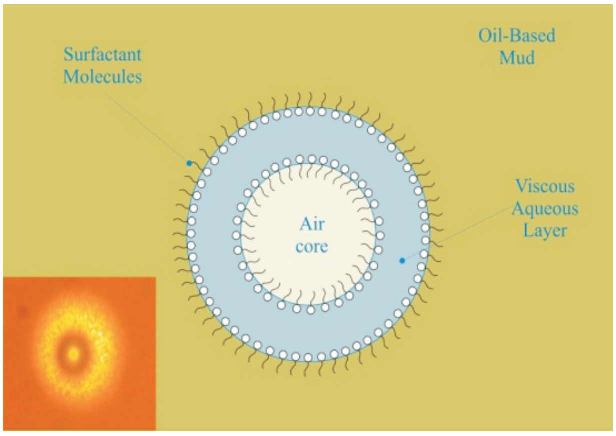

Figure 3 Strucure of oil-based aphron
Slika 3. *Struktura afrona u fluidu na bazi ulja*

Aphrons are very stable in diferent working conditions. Their stability depends on thickness and viscosity of the encapsulating shell. The shell (aphron viscosity film) must have a certain minimum thickness. This is important because aphrons in circulation change their volume with pressure change according to Boyle's Law. If shell becomes excessively thin, as may happen on expansion when exposed to a very large pressure drop, it will probably break (Sebba, 1987.; Growcock et al., 2003.). The water/film shell is not stable if it is thinner than four microns or thicker than 10 microns (Ivan et al., 2001.). Apart from thickness, very important criterion for aphron stability is shell viscosity. The shell must have a minimum viscosity to prevent phenomenon known as the "Marangoni effect" that cause diffusion of water out of the shell into the bulk liquid. This thins and destabilizes the shell (Shebba, 1987.). The rate of transfer of water is inversely proportional to shell viscosity. Therefore, addition of a viscosifier such as biopolymer is required. The viscosifier also serves to slow the flow of bulk fluid into loss zones (White et al., 2003.; Ivan et al., 2002.).

The aphrons can survive exposure to elevated pressures much better than conventional bubbles (Figure 4). When compressed to 3,55 MPa and maintained at that pressure, all three bubbles immediately shrank, from original size of about 250 µm at atmospheric pressure, to about 150 µm. As shown in Figure 4, the enhanced aphron survived more than 30 minutes, whereas the standard aphron disappeared in less than 10 minutes, and the conventional bubble disappeared within 2 minutes (Growcock et al., 2006. and 2007.; Belkin et al., 2005.).

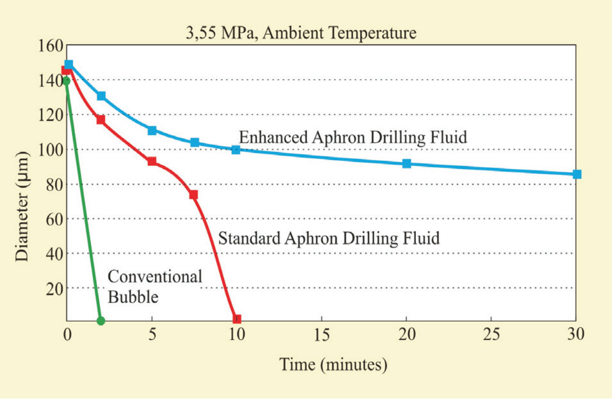

Figure 4 Longevity of aphrons at elevated pressure
Slika 4. *Postojanost afrona na povećanom tlaku*

Over short period of time, aphrons can survive compression and decompression (Figure 5). Aphrons can survive compression to at least 27,7 MPa (Ivan et al., 2002.; White et al., 2003.; Belkin et al., 2005.; Growcock et al., 2006.). Aphron size have a big influence on its survivability and structure stability. Large aphrons (> 100 µm diameter) appear to be able to survive much better than small aphrons (Belkin et al., 2005.). When aphrons become smaller than about 50 µm in diameter they become less stable.

Aphron can suvive rapid compression and decompression when aphron based fluid circulated through system. As shown in Figure 5 rapid compression of an aphron drilling fluid from 0 MPa to 20,79 MPa, followed by decompression back to 0 MPa, results in essentially full regeneration of the aphrons (Belkin et al., 2005.; Growcock et al., 2005.; Popov et al., 2005.). Rapid pressure cycling of aphron drilling fluids leaves most aphrons intact.

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."

The encapsulated air within an aphron is compressed when circulated downhole. The micro-bubble volume decreases and internal pressure increases to an extent approximately proportional to the external pressure being applied. The combination of increasing pressure and temperature serves to energize the aphron.

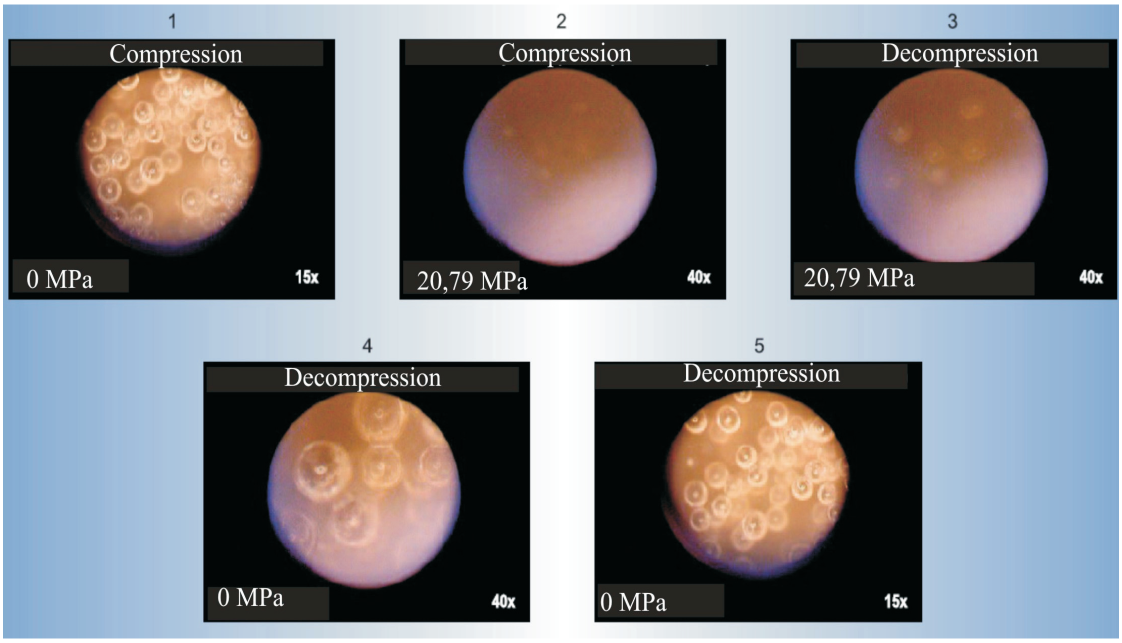

Figure 5 Surviving of Aphrons at Compression and Decompression
Slika 5. *Postojanost afrona uslijed povećanja i smanjenja tlaka*

Aphron drilling fluids

The initial and predominant type of aphron drilling fluid used in the field has been a polymeric water-based system, although a clay water-based alternative and a non-aqueous-based aphron drilling fluid, such as ester-based aphrons, also have been developed (Grewcock et al., 2007.). Tables 1 and 2 show the composition of typical water-based and oil-based aphron drilling fluids. Both of these fluids consist of a viscosifier, aphron generator, aphron stabilizer and filtration control agent. The major difference between the two fluid systems is the continuous phase wich is water (fresh water or brine) in water-based aphron system, and oil or synthetic fluid in oil-based aphron system (Ivan et al., 2001.; Ivan et al., 2002.; Growcock et al., 2004.[a]; Growcock et al., 2003.).

The high-LSRV base fluid consists of a high-yield stress-shear-thinning (HYSST) polymer coupled with filtration control agents that create and stabilize the aphrons within continuous phase. An aphronizer surfactant is incorporated to achieve the desired concentration of micro-bubbles, which typically range from 8 to 14 % by volume (Ivan et al., 2001.). As the concentration builds, it is not uncommon to observe an increase in the Brookfield LSRV to between 120 000 and 160 000 mPa·s (Ivan et al., 2001.).

Table 1 Composition of a typical water-based aphron system
Tablica 1. *Sastav tipične isplake na bazi vode s afronima*

Component	Function	Concentration
Fresh water/brine	Continuous Phase	0,97 m^3/ m^3
Soda ash	Hardness Buffer	0,71 kg/m^3
Biopolymer blend	Viscosifier	14,26 kg/m^3
Polymer blend	Filtration Control Agent and Thermal Stabilizer	14,26 kg/m^3
pH buffer	pH control	1,43 kg/m^3
Surfactant	Aphron Generator	2,85 kg/m^3
Biocide	Biocide	1,19 l/m^3
Polymer/Surfactant Blend*	Aphron Stabilizer	2,85 kg/m^3
Polymer*	Shale Inhibitor	2,85 kg/m^3
Oligomer*	Defoamer	2,85 kg/m^3

* Optional component

Table 2 Composition of a typical oil-based aphron system
Tablica 2. *Sastav tipične isplake na bazi ulja s afronima*

Component	Function	Concentration
Oil or synthetic fluid	Continuous phase	0,97 m^3
Clay or Polymer Blend	Viscosifier	42,79 kg/m^3
Surfactant	Aphron Generator	2,85 kg/m^3
Water	Polar Activator	28,53 kg/m^3
Polymer*	Filtration Control Agent	2,85 kg/m^3
Polymer/Surfactant Blend*	Aphron Stabilizer	2,85 kg/m^3

* Optional component

Comparison of physical properties of typical water-based and oil-based aphron systems is presented in table 3 (Ivan et al., 2001.; Growcock et al., 2004.[a]; Growcock et al., 2003.).

Viscosity. The low-shear-rate viscosity (LSRV) of aphron drilling fluids is considerably higher than that of conventional reservoir drilling fluids. The LSRV plays an important role in the invasion of aphron drilling fluid into formation and should always be maintained at more than 50 000 mPa·s. As the fluid slows because of radial flow and the bridging action of the aphrons, its shear rate decreases and its viscosity rises. If the LSRV drops, it is higly recommended that drilling be suspended until the mud properties are restored. The presence of the aphrons does not significantly affect viscosity (Growcock et al., 2003.).

Corrosion. Corosion is generally a major problem when drilling with air systems and areated fluids. Concerns over corrosion and well control have traditionally led to attempts to minimize air entrainment. The air in aphron drilling fluids is purposely incorporated into the bulk fluid during addition of product, but at a very low concentration. The surfactants in the fluid convert the entrained air into aphrons. The oxygen from the air in the aphron cores, indeed even the oxygen dissolved in the base fluid, is lost via chemical reaction with various component in the fluid. This process usually takes minutes and result in the aphrons being filled primarily with residual nitrogen. Thus, corrosion of tubulars and others equipment by aphrons is negligible. This was proved in the field where in spite of the lack of a specific corrosion program, corrosion rates were very low in wells even with the presence of high concentrations of H_2S (Kinchen et al., 2001.).

Fluid invasion control. Various laboratory techniques were applied to determine how aphrons affect flow through permeable and fractured media. When the drilling fluid enters a formation, the aphrons expand to a small extent and, more importantly, move forward rapidly by means of “bubbly flow” to concentrate at the fluid front and create a “microenvironment” that separates the borehole from the formation pressures.

Capillary pressure resists invasion of a hydrophobic micro-bubble into a water-wet interconnected microfracture/pore network in permeable formations (White et al., 2003.; Schaneman et al., 2003.; Ivan et al., 2001.).

The resistance to flow of aphrons and the carrier fluid into formation openings, i.e. the effectiveness of the seal formed by the aphrons, is dependent on the size of the openings and the degree of hydrophobicity of the aphron outer shell. Small openings and strongly hydrophobic/lipophilic aphrons promote sealing. Conversely, very large openings, e.g. fractures, will generate little or no capillary pressure and, hence, no seal may be possible except at the fracture tip (Ivan et al., 2001. and 2002.).

Table 3 Physical properties of typical unweighted aphron drilling fluids
Tablica 3. *Fizička svojstva neotežanih afronskih isplaka*

Fluid properties	Water-Based	Oil-Based
Density (kg/m^3)	1027	812
Plastic viscosity (mPa·s)	9	15
Yield Point (Pa)	22	33
Gel Strenght 10 s/10 min (Pa)	13/16	22/25
API Fluid loss (cm^3/30 min)	9	negligible
LSRV at 0,06 s^{-1} (mPa·s)	60 000+	50 000 +

Once the drilling bit exposes a depleted formation, aphrons are brought together within the openings of low-pressure zones. There, a portion of the energy stored within each aphron is released, causing it to expand. The expansion continues until the internal and external pressures on the wall of the aphron are in balance. Figure 6 illustrates this energizing process (Ivan et al., 2002.; Rea et al., 2003.; Growcock et al., 2004.[b]; Spinelli et al., 2006.).

As the energized micro-bubbles are crowded into formation openings, external Laplace forces increase dramatically, causing aggregation of the micro-bubbles and an increase in low-shear-rate viscosity (LSRV). The micro-environment created by this phenomenon forms a solids-free bridge. Another benefit of the non-conventional internal seal is its effect on differential sticking. The seal exhibits a gradual pressure drop (Figure 6) from the annulus to the seal interface with the reservoir fluids. This pressure absorption profile sufficiently alters the near-bore pressure drop environment, which effectively negates differential sticking. This translates into a considerable reduction in risk when employing costly downhole tools during well construction in high-annular and low reservoir-pressure applications (Rea et al., 2003.; Ivan et al., 2002.). Always when wellbore pressures exceed formation pressures, aphrons will migrate with the pressure gradient from the wellbore to the formation. If wellbore pressure is lowered to below the fomation pressure the aphrons will again move with the pressure gradient, from the formation into the wellbore. Evan with an unweighted fluid, it is important to consider the surfactant depletion as it is consumed on the drill cuttings and/or in the borehole. Inadequate surfactant concentration can lead to increased downhole losses.

Field experience

The aphron drilling fluid technology has been successfully applied in drilling vertical, horizontal and inclined well, as well as in completion and workover operations in South America, North America, Africa, Far East, Eastern Mexico, Venezuela, North Sea, North Texas, and Wast Texas (MacPhil et al., 2008.; Growcock et al., 2006. and 2007.; Rea et al., 2003.; White et al., 2003.; Ramirez et al., 2002.; Ivan et al., 2001.; Brookly, 1998.). From the first application up to now, aphron-base technology used The Hundreds of wells worldwide have been successfully drilled through depleted reservoirs in mature oil and gas fields, high-permeability formations and micro fractured rocks (Ivan et al., 2001.; Growcock et al., 2004.). Table 4 presents different data collected from the published literature regarding field experience in applying aphron fluid technology.

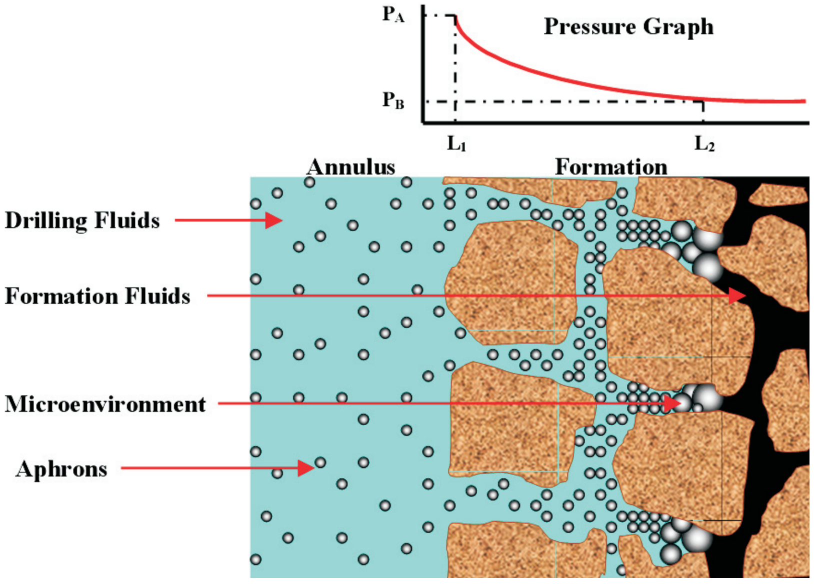

Figure 6 Aphrons bridging mechanism
Slika 6. *Mehanizam premošćenja pomoću afrona*

Conclusion

Depleted or low pressure reservoirs represent a great challenge for drilling, completion and workover operations. Often, these reservoirs are composed by fractured interbeded layers with different pore pressure, usually depleted water-wet sands and pressured shale. There are several problems related with this type of reservoirs like fluid loss control, stabilization of multipressure sequences with one fluid, possible differential sticking and formation damage.

Table 4. Field application data of aphron based fluids
Tablica 4. *Podaci o primjeni fluida s afronima u praksi*

Location	Operation (number of wells)	Formation	Problem	Benefit	Source
South America	Drilling under-pressured zones (3 wells)	Highly permeable sand	Lost circulation, borehole instability	Successfully coring, wire-line logging and cementing	Growcock et al, 2006. and 2007.
Eastern Mexico (The Tajin area)	Workover and re-completions operation (3 wells)	Oil producing depleted sands interbedded with reactive shales	Loss circulation, gas influxes	Minimal invasion, safe working environment, reduced environmental risk and cost reduction	Rea et al 2003.
Lake Maracaibo, Venezuela	Drilling low-pressure zones (9 wells)	La Rosa formation (sands, and alternating sand and shale)	Lost circulation, borehole instability, formation damage, deficient cementation	Excellent hole cleaning, inhibition and fluid invasion control	Ramirez et al. 2002. , Rea et al. 2003.
North Sea (Dutch sector)	Drilling throughout two reservoirs with different pressures	Claystone between two sand formations	Lost circulation, risk of fracturing reservoir with lower pressure, formation damage.	Successfully completed operation	White et al. 2003.
West Texas (Fusselman)	Horizontal re-entry drilling (1 well)	Fracture formation	Mechanical problems with the small tools, large fracture and lost complete returns	Excellent hole conditions, no drag, fill or instability	Brookly 1998.
North Texas	Drilling (2 wells)	Dolomitic reef zone with interconnected large vugs	Lost circulations	Successfully drilling and completion	
	Re-entry drilling (1 well)	Monterey shale (highly fractured and unstable)	Lost circulation, borehole instability	Drilling without any problems and running the slotted liner to TD, no formation damage	
	Drilling (1 well)	Sisquoc sand (unconsolidate, permeable sand)	Borehole instability and formation damage	Drilling was completed without problems, and slotted liner was successfully run	
California (near Bakersfield)	Drilling	Highly fractured sand	Mud losses in low pressure reservoir, formation damage	Minimized downhole losses and successful drilling to total depth	Ivan et al. 2001.
New Mexico, Indian Basin field	Drilling (7 wells)	Dolomite and Limestone formation containing large vugs	Lost circulation, source gas	Low corrosion, drilling without loses, no need for acid stimulation	Schaneman et al. 2003.; Kinchen et al. 2001.
Alberta	Completion and workower (1 well)	Gas producing sandstone	Sour gas, enable well completion	Successful completion and workower operations	MacPhail et al. 2008.
	Completion (1 well)	Gas producing dolomitical Limestone	Depleted reservoir, losses of kill fluid, formation damage	Successful workower operations and fluid invasion control	
Alberta	Workower (2 well)	Conglomerate sands	Fluid leakoff, high fracture treating pressure	Preventing fluid leakof under high differential pressures	

Solving these problems requires additional time and cost, especially on the rig with conventional equipment. Using aphron based technology depleted reservoirs which are very expensive to drill underbalanced or with other remediation techniques, can be drilled overbalanced. Aphron drilling fluids protect producing formation by minimizing formation damage, because of the excellent compatibility of the drilling fluids with produced fluids, and because of the lack of affinity of aphrons for each other and for mineral surfaces. Although the technology has been successfully used worldwide choosing the appropriate formation is critical. The ideal targeted formation for the aphron based fluid is one with highly tortuous pore throats or fractures, which will permit the aphron to form a bridge.

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