R&D validates effectiveness of aphron drilling fluids

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RECENT WORK HAS helped validate an innovative drilling fluid technology that incorporates uniquely structured micro-bubbles of air called "aphrons" to recover hydrocarbons from mature and highly depleted reservoirs.

An investigation partly funded by the DOE's Office of Fossil Energy is laying to rest many of the concerns surrounding the use of entrained air in drilling fluids and, in the process, is sanctioning use of a novel fluid technology that has been proven highly successful in drilling depleted reservoirs and other low-pressure formations.

Recovering depleting reserves from the increasingly numerous mature oil and gas reservoirs has been, until now, an uneconomical proposition.

Typically, the formations above and below these producing zones have much higher pore pressures and require higher fluid density for stabilization.

However, exposing depleted zones to a high-density fluid can result in considerable loss of whole drilling fluid and differential sticking.

Furthermore, pressured shales often are interbedded with depleted sands, thus requiring stabilization of multiple pressure sequences with a single drilling fluid.

Drilling these zones safely and inexpensively is very difficult with conventional rig equipment.

Preventive measures often entail adding either a low concentration plugging agent to the entire circulating system, or remediation with a 50 to 100 bbl pill containing a plugging agent or settable material when the rate of loss of drilling fluid exceeds a certain threshold level.

Unfortunately, these preventive measures usually are unsatisfactory when it comes time to clean up the formation to optimize production.

Consequently, drilling depleted or multiple pressure zones with a low-density fluid has become an increasingly popular alternative, even though doing so carries the risks of wellbore collapse and blowouts.

The new aphron fluid technology does not involve drilling underbalanced nor does it require use of plugging agents. Nonetheless, it is effective at mitigating loss of fluid and differential sticking with minimal risk of formation damage and pressure-control problems.

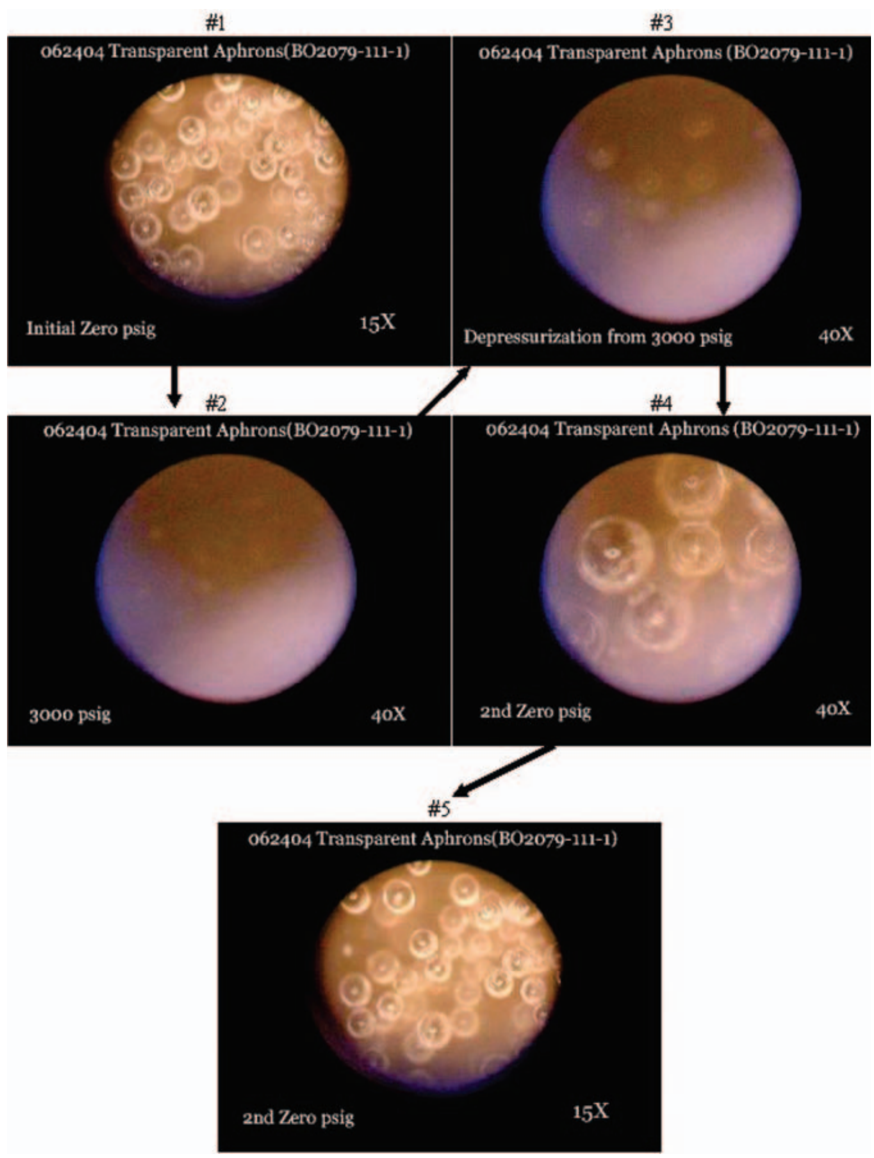
PROPERTIES OF APHRONS

Because of concerns over corrosion and well control, drillers generally discourage entrainment of air in drilling fluids; indeed, they often go to substantial lengths to eliminate air altogether.

Consequently, the purposeful incorporation of air, as in aphron drilling fluids, is looked on with some apprehension.

Recent laboratory work conducted under the auspices of the DOE has served to broaden understanding of the workings of aphron drilling fluids and has helped eliminate many of these concerns.

Aphrons are constructed by entraining air in the bulk fluid with standard drilling fluid mixing equipment, thus reducing the safety concerns and costs associated with the high-pressure hoses



Survivability of aphrons during compression/decompression to 3,000 psi. Rapid compression of an aphron drilling fluid from ambient pressure to 3,000 psi followed by decompression back to ambient pressure results in essentially full regeneration of the aphrons.

and compressors commonly utilized in underbalanced air or foam drilling.

Although each application is customized to meet individual operator needs, the drilling fluid system generally is designed to contain 12-15 vol % air, and the aphrons so generated are thought to be sized or polished at the drill bit to achieve a size less than 100 μm diameter, which is typical of many bridging materials.

These novel fluids possess two chief attributes that serve to minimize fluid invasion and damage of producing formations.

First, the base fluid is very shear-thinning and exhibits an extraordinarily high LSRV (low-shear-rate viscosity) with very low thixotropy; this unique viscosity profile reduces the flow rate of the fluid dramatically upon entering a loss zone.

Second, during fluid invasion in a permeable formation, aphrons experience bubbly flow, which sends them rapidly to the fluid front where they concentrate and form a soft internal seal that reduces losses further.

Aphrons are capable of carrying out this task by virtue of their high survivability at elevated pressures; conventional bubbles do not survive high pressures.

Furthermore, aphrons appear to have little affinity for each other or for rock surfaces, thereby enabling them to be produced back with relative ease.

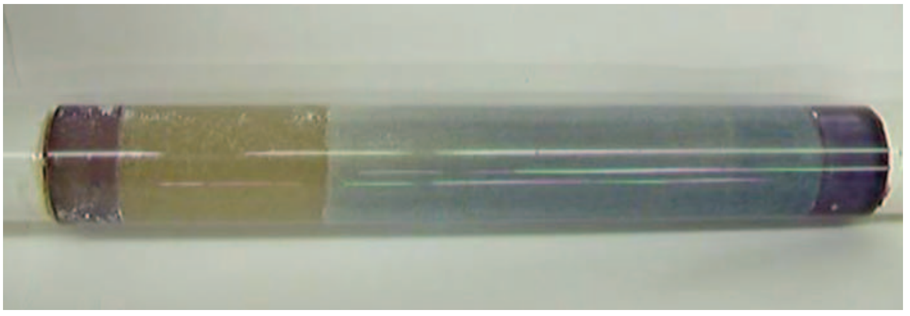
The key to the high stability of an aphron is the protective shell that surrounds the air core.

In contrast to a conventional air bubble, which is stabilized by a surfactant monolayer, the shell of an aphron is thought to consist of a much more robust surfactant tri-layer.

This tri-layer consists of an inner surfactant film enveloped by a viscous water layer and an outer bi-layer of surfactants; the latter provides rigidity and low permeability to the structure while imparting some hydrophilic character.

Aphrons have been found to survive compression to at least 4000 psi (27.7 MPa) for significant periods of time. Conventional bubbles, on the other hand, do not survive long past a few hundred psi.

When a fluid containing bubbles-conventional or aphrons-is subjected to a sudden increase in pressure above a few hundred psi, the bubbles initially shrink in accordance with the modified Ideal Gas Law.



This photo demonstrates the bubbly flow of aphron drilling fluid in a 20/40 sandpack.

However, conventional bubbles begin to lose air rapidly via diffusion through the bubble membrane and the air dissolves in the surrounding aqueous medium.

Aphrons also lose air, but they do so very slowly, shrinking at a rate that depends upon fluid composition, bubble size and rate of pressurization and depressurization.

Compression will reduce a bubble of 100 mm diameter at atmospheric pressure to 38 mm when subjected to a pressure of 250 psi (1.8 MPa), and 19 mm at 2,500 psi (17.3 MPa).

However, the biggest effect of pressure by far on the fate of a bubble is increased gas solubility. Henry's Law states that the solubility of a gas is roughly proportional to the pressure.

For example, when a fluid containing 15 vol % entrained air at ambient pressure is compressed to 250 psi (1.8 MPa), all of the entrained air becomes soluble.

If the stabilizing membrane surrounding the bubble is permeable, the air will diffuse into the surrounding medium and go into solution. This is indeed what happens with ordinary bubbles; within seconds, they shrink and disappear.

Aphrons possess a much less permeable membrane, so they do not lose their air as readily; when aphrons are subjected to a pressure of 250 psi (1.8 MPa), they remain stable indefinitely.

Over short periods, aphrons will survive compression to much higher pressures. Rapid compression of an aphron drilling fluid from ambient pressure to 3,000 psi (20.8 MPa) followed by decompression back to ambient pressure results in essentially full regeneration of the aphrons.

However, the oxygen in aphrons, indeed, even the oxygen dissolved in the base fluid, is lost via chemical reaction with various components in the fluid, a process that usually takes minutes and results in nitrogen-filled aphrons.

Thus, corrosion of tubulars and other hardware by aphrons is negligible. Even at ambient temperature and pressure, the oxygen in solution in an aphron drilling fluid disappears within hours after preparing the fluid.

By contrast, in a typical clay-base or polymer-base fluid, the concentration of oxygen in solution remains relatively constant.

Wettability tests indicate that aphrons have very little affinity for each other or for the mineral surfaces in rock formations encountered during drilling. This bond between the bubbles is thought to result from imperfect development of the aphron shell.

However, the bubbles do not coalesce, but rather separate within a few seconds. The same occurs for aphrons that are forced onto a limestone or silica surface: mild stirring causes the bubbles to separate from the surface.

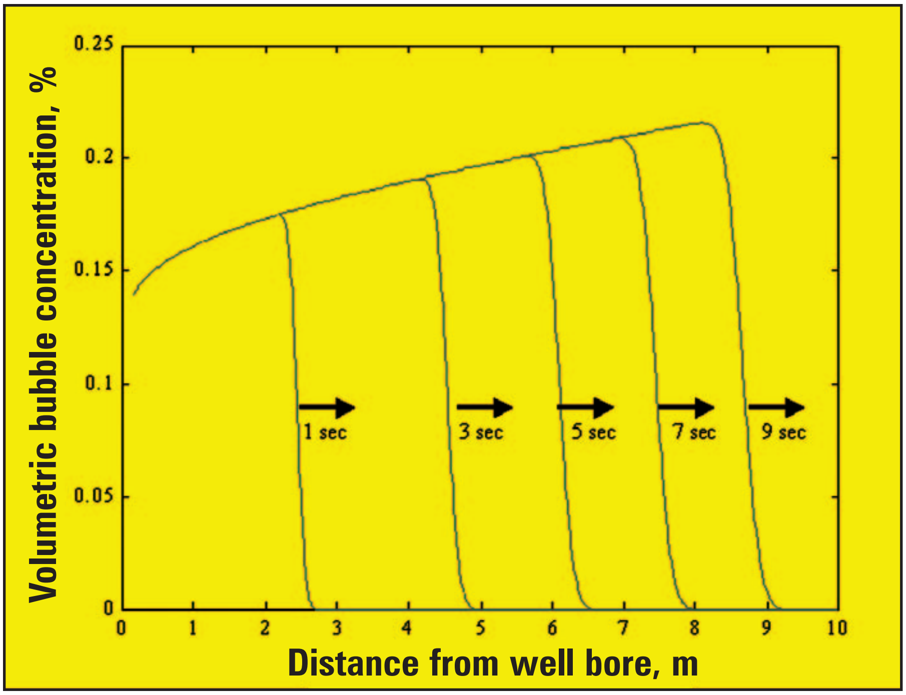
Thus, aphrons resist agglomeration and coalescence and are expected to be pushed back out of a permeable formation easily during production, thereby minimizing formation damage and cleanup.

FORMATION INVASION

For a typical aphron drilling fluid, aphrons are present at such a low concentration that they have a negligible effect on fluid rheology in the wellbore.

The fluid is highly shear-thinning and roughly follows a Power Law model even down to a shear rate as low as 0.01 sec^{-1}.

At the same time, steady-state values of shear stress are reached within seconds



This graph illustrates concentration profiles of air at various times after the initial fluid invasion.

after changing shear rate, thus, the aphron drilling fluids exhibit very low thixotropy.

More detailed analysis of steady-state viscosimetry data shows that the Herschel-Bulkley model (also known as the "Yield Power Law" model) fits even better, but the best simple model fits are a Carreau model and a Double Power Law model.

Based on these comparisons, the Carreau model with Yield was incorporated into a flow model for the drilling fluid in the annulus and permeable zone.

The main characteristic of this model is that it predicts a constant viscosity at low very low shear rate and a constant viscosity at high shear rates.

For intermediate values of the shear rate, it exhibits a power-law like, highly nonlinear relationship.

Suppose that an axially symmetric wellbore of radius 0.15 m is drilled in a uniform, isotropic reservoir with 2.5 Darcy permeability.

The pressure at the wellbore is 2500 psi (17.3 MPa), and the pressure at a distance of 10 m into the reservoir is 500 psi (3.5 MPa).

The equations governing the flow are Darcy flow through the formation and the conservation of mass.

After 24 hours, the aphron fluid has invaded the reservoir to a distance of 10.7 m from the wellbore if the fast flow mode is assumed.

If, however, the slow flow mode is assumed, the fluid has invaded only 0.43 m of the reservoir.

These two numbers give the bounds in which the invasion of the aphron fluid can happen.

The difference is significant, and there is a clear need to establish if and when the regime changes from fast to slow.

Note that this drastic change in the invasion depth is only due to a change in the viscosity of the fluid from high to low shear rates.

Simulations using a base fluid with aphrons shows that in the presence of a pressure gradient, a bubble will experience unbalanced forces on its surface and experience "bubbly flow."

As a result, it will move relative to the fluid and in the direction of the pressure gradient.

The relative velocity of a bubble subjected in a pressure gradient can be related to the Stokes Equation, which is often invoked for gravity-driven settling of weighting material or separation of bubbles.

Bubbly flow is proportional to the pressure gradient, inversely proportional to the fluid viscosity and proportional to the square of the bubble radius.

In permeable rock under downhole conditions, accumulation of aphrons at the fluid front can create a barrier to flow of liquid or increase the viscosity of the fluid.

In either case, increasing the concentration of aphrons slows invasion of the fluid.

In modeling this, a constant concentration of about 0.15 vol % of the bubbles was assumed at the wellbore. As the bubbles are released for the first time at the wellbore, they form a front, which starts moving away from the wellbore.

Their velocity is a sum of both the fluid velocity and their relative velocity (2) with respect to the fluid.

Since at different distances from the wellbore the fluid velocity and pressure gradients are different, the bubbles change speed, generally slowing down as they move away.

Furthermore, as the pressure decreases, they expand and increase the volumetric concentration of gas.

To simulate this, the volumetric bubble concentration was computed using a first-order upwind finite difference scheme for bubbles with initial radius 100 mm at several instances of time. The bubble concentration away from the wellbore increases very slowly.

However, the bubble profile travels away from the wellbore very quickly, with a speed on the order of meters per second.

This high speed appears to be due to the large pressure gradient, which is of about 107 Pa/m near the wellbore. Consequently, as soon as fluid penetrates the permeable rock, bubbles move to the fluid front and concentrate there to form a soft seal.

Since the volume ratio of liquid/air entering the reservoir is constant with time, the thickness of this highly concentrated bubble layer relative to the fluid invasion depth is also nearly constant.

For an invasion depth of 10 m, the bubble layer has a thickness of 2-10 cm, depending on the concentration of bubbles in the layer.

This bubble layer serves as a barrier to flow of the liquid and effectively slows the rate of invasion of drilling fluid. ■