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Successful Hydrajet Acid Squeeze and Multifracture Acid Treatments in Horizontal Open Holes Using Dynamic Diversion Process and Downhole Mixing

M.J. Rees and A. Khallad, PetroCanada Oil and Gas, A. Cheng, K.A. Rispler, J.B. Surjaatmadja, and B.W. McDaniel, Halliburton Energy Services, Inc.

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Abstract

Effective stimulation of wells with long, openhole horizontal completions is generally considered a difficult task, especially in low-permeability carbonate reservoirs that require deep penetration with live acid. Because the creation of multiple effective fractures, the opening (etching) of existing fractures, or the creation of extensive wormholes is generally desired, this task becomes even more difficult, time-consuming, and expensive if conventional acidizing processes are used. If the live acid is not channeled properly, it will be spent rapidly at unwanted locations, often greatly enlarging the fluid-entry point. Under such circumstances, creating etched fractures or wormholes of any significant lengths can be nearly impossible.

A relatively new hydrajet fracturing process can be used to solve this problem. This process can be used in two ways: (1) dynamic fluid energy is used to divert flow into a specific fracture entry point to initiate a fracture at the intended location with live acid directed into this fracture plane, (2) high-pressure downhole mixing is used to create foam for high-intensity acid squeezes. This technique typically uses two independent fluid streams, one in the treating string and another in the annulus. The two fluids (if dissimilar) are mixed downhole at a tremendously high energy to form a homogenous mixture.

This paper discusses and compares the results of conventional acid treatments with various styles of hydrajet fracture-acidizing treatments performed in several openhole horizontal wells within two different areas of the same formation. The novel use of the downhole mixing feature is also discussed.

Introduction

Mineral and organic acids have been used to stimulate oil- and gas-producing formations for more than 100 years. In carbonate formations, which have high acid solubility, using acid fluids at fracturing pressures predates most professionals currently active in stimulation technology. Over the years, several effective acidizing formulations, chemicals, additives, and placement processes have been developed. During many such developments, laboratory and field studies were combined to develop specific treatment fluids and processes for a particular formation or reservoir.

In long, openhole completions (primarily horizontal or highly deviated wellbores), large exposed surfaces tend to consume acids or other chemicals prematurely or at only a few locations along the wellbore. Acids are likely spent at locations where they first contact the formation or at more highly reactive areas. In such cases, different delivery techniques must be used to place the acid at the desired destination. Ported subs and coiled tubing (CT) have sometimes been used successfully for such placements, and other more novel approaches have reportedly been used in openhole carbonate completions.[1-2]

Successful acid treatments in wells with long openhole wellbores depend on the following conditions:

- Live acid reaches the desired location along the wellbore.
- Live acid reaches far into the formation for adequate etching or wormholing to achieve sufficient near-wellbore or frac-

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In long, openhole completions (primarily horizontal or highly deviated wellbores), large exposed surfaces tend to consume acids or other chemicals prematurely or at only a few locations along the wellbore. Acids are likely spent at locations where they first contact the formation or at more highly reactive areas. In such cases, different delivery techniques must be used to place the acid at the desired destination. Ported subs and coiled tubing (CT) have sometimes been used successfully for such placements, and other more novel approaches have reportedly been used in openhole carbonate completions.[1-2]

Successful acid treatments in wells with long openhole wellbores depend on the following conditions:

- Live acid reaches the desired location along the wellbore.
- Live acid reaches far into the formation for adequate etching or wormholing to achieve sufficient near-wellbore or fracture conductivity.
- Isolating procedures are used to ensure that the acid is only placed within the target area.

The hydrajet stimulation technique can be used to achieve these goals. One variation of this technique, which uses the hydrajet fracturing process,[3-6] has been used in more than 400 fractures in over 40 wells (both fracture-acidizing and proppant-fracturing applications). This paper describes an expansion of the previous technology[7] to use high-pressure jetting energy to perform some or all of the following tasks simultaneously: perforation, fluid delivery, fracture initiation, fracture extension, tortuosity reduction, chemical mixing, and regional isolation.

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Hydrajet Fracturing Technology

Previous publications provide detailed discussions about using hydrajet fracturing to create substantial fractures. The use of elevated annulus pressure to improve fracture extension is an important component of this technology and is also well known.[3-5] Even when the annulus pressure is below the fracture-gradient pressure, small hydraulic fractures can be created by the elevated pressures resulting from stagnation pressure within the jetted-out tunnel or notch in the formation rock. Let us consider the jet and wellbore wall shown in **Fig. 1**. In this figure, high-pressure fluid inside the tool (T) accelerates through the jet (J), as shown in Equation 1:

$$\frac{V^2}{2}+\frac{p}{\rho}=C \text{..(1)}$$

where
V = fluid velocity
P = pressure
ρ = mass density

Depending on the fluid's viscosity, the velocity of the fluid exiting the jet (at a 5,000-psi pressure differential) can be approximately 430 to 650 ft/sec. When this jet is at a distance of d [or $d+Dd$, including the notch (Fig. 1)], "flaring" of the jet and enlargement of the notch reduce the effective stagnation pressure. However, as we reduce the distance to a value near zero, the stagnation pressure will be similar to the original jet pressure (minus some inefficiencies). At any time during jetting, the highest pressures anywhere within the entire openhole section will be inside the notch or cavity that is currently being jetted.

High-Energy Downhole Mixing

Through the use of the annulus between the coiled tubing and the production tubulars, hydrajet stimulation technology can deliver two independent fluid streams downhole. The composition of the annular fluid can vary depending on the type of stimulation desired. In the case of hydrajet fracture stimulation, the annular fluid is generally used to control annular pressure and aid in the creation of the fracture. In the case of hydrajet squeeze stimulation, the fluid is used to create a high-quality downhole foam that assists in effective mechanical diversion. The fluid used for hydrajet squeeze stimulation is generally a gas, whereas hydrajet fracture stimulation has used a variety of fluids, including clean fracturing fluids, liquids that chemically control clay stability, and plain, low-cost fluids (provided that they do not exhibit excessive fluid loss in the openhole annulus). Regardless of type, all annular fluids are mixed with the fracturing fluid, and part of this mixture is flowed into the fracture. The remainder of the fluid will be lost to the formation.

Annular fluids can be engineered to perform various functions, such as modifying pH on location or creating a rapid reaction in the fracturing fluid. As mentioned earlier, one practical application of gaseous annular fluids is the creation of foams if sufficient mixing energy is available. Generally, foams are generated when one flow stream containing gas is mixed with another flow stream containing liquid. Foaming agents are usually mixed with liquid to promote effective foaming, and foam generators are used to improve the texture quality of the foam (**Fig. 2**).

Foam generators improve foam texture by accelerating one of the fluids to a high velocity and injecting the fluid into a stream of the other fluid. In surface operations, acceleration is most easily accomplished with the gaseous portion. The gas accelerator can be a nozzle(s) or other pressure-reducing device, such as a porous material or channel. For pressure differentials in the range of 200 to 1,000 psi, we can achieve gas velocities of approximately 350 ft/sec, thus creating the high-energy shear necessary for foam development. With hydrajet fracturing, the same situation exists downhole: a high-energy jet enters the jetted cavity (Fig. 1), which contains compressed gas. The jet pressure differential is generally 5,000 psi, creating a jet velocity of approximately 650 ft/sec. The combination of the high-velocity differential and the high energy level causes effective foam development.

Stimulation with CO_2 and N_2 Foams

For more than 20 years, foamed fluids have been used during hydraulic fracturing, fracture acidizing, and matrix acidizing treatments for reducing fluid loss, carrying proppants into the formation, and reducing liquid loads on the formation (reducing formation damage). During acidizing, foamed fluids also help retard the reaction rate of the acid with the formation, allowing live acid to penetrate further into the formation matrix or fracture. Generally, slowing the reaction rate may also promote "wormholing," a condition that can improve production. Finally, foamed fluids can be useful for cleaning the wellbore after the stimulation treatment.

The creation of fractures and the transportation of proppant into the fracture are enhanced by the viscosity of the foamed fluid. Foam viscosity depends on several variables, including foam quality, the viscosity of the external phase, and the texture (or bubble-size distribution) of the foamed fluid. Foams exposed to shear for a sufficient time will equilibrate to a bubble-size distribution that is characteristic of shear rate. The texture of a foamed fluid is also influenced by surfactant volume and type (composition). Surfactant concentrations must be adequate for stabilizing the foam under dynamic conditions.

Studies have shown that the texture of a foamed fluid also influences its diversion capabilities. Higher shear rates, specific surfactant concentrations, and high pressures create finer-textured aqueous foams, which provide better diversion. The nature of the liquid phase also influences the texture of foamed fluids. The larger bubble sizes exhibited by hydrocarbon and methanol foams result in greater sensitivity to degradation at high shear rates.[10-11]

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Acid Treatment Tools and Processes

Various methods for placing acid in an openhole (horizontal) wellbore are described in the following paragraphs.

Pumping through Casing. Pumping acid through the casing is possibly the easiest way to place acid downhole at high injection rates. However, this practice is seldom effective for wells with long openhole sections. In many wells, the acid will generally be spent at the point of entry into the open hole, often close to the heel section, leaving the remainder of the wellbore relatively untreated. This can create a large void that may later cause well collapse, or make it difficult to get tools downhole past this section at a later time.

Spot Placement. Spot placement of acid through coiled tubing can sometimes be effective for removing near-wellbore damage. The acid can often be placed almost evenly along the openhole section. Tools are not generally required, but gravity segregation problems and varying acid reactivity of the formation often limit the effectiveness of this technique.

Washing. Although acid-washing procedures are similar to spot-placement procedures, acid washing involves using jet nozzles to wash the wellbore surface. This process is usually more effective at removing the damage caused by procedures such as drilling. **Figs. 3** and **4** show sample jet-nozzle assemblies; however, jet positions and sizes may differ with the tool chosen for a particular job. When an acid wash is performed, differential pressures across the jets are generally low and do not reach levels high enough to initiate fracturing or effective shear for foam generation. Summers[8] and Momber[9] have shown that effective wash pressures are primarily affected by the tensile strength of the filter cake or the grain of the cementitious material. Consequently, effective wash pressures are generally less than 2,500 psi. Often, rotating heads running at high speeds are used to more effectively clean the wellbore surface.

Squeezing. To achieve a squeeze condition, a method similar to washing is used, but the annular area between the formation and the treating string is pressurized or shut in, forcing some of the acid to penetrate the matrix. The stability of foam generated at surface during these squeezes is questionable at the high temperatures (250°F) exhibited by some of the case wells. Consequently, the effectiveness of the diverting properties of the downhole foams is questionable.

Hydrajet Squeezing. Similar to conventional squeezing (described in the previous section), hydrajet squeezing employs pressurization of the annulus while the primary treating fluid (acid) is pumped down the CT. However, hydrajet squeezing takes this process one step further; CO_2 or a CO_2/N_2 mixture is pumped down the annulus at a high rate, allowing downhole foam generation. A high-pressure drop (3,000 psi) nozzle is used to create the shear necessary for creating this foam.

In addition to allowing acid to be pumped at extremely high rates, this technique allows operators to easily change the quality of the downhole foam by changing the rates at which the gas and acid are pumped. This technique simplifies the placement of foam plugs in the open hole and allows high volumes of acid to be pumped over short periods.

Fracture Acidizing. Fracture acidizing involves creating hydraulically induced fractures for significant penetration into the formation, where acid can react with the fracture face to create an uneven or irregular fracture surface, resulting in a conductive path between the fracture faces (**Fig. 5**). In higher-temperature reservoirs, additives (including gases) are often used to retard the acid's reaction, allowing etching to occur farther from the wellbore.

With the hydrajet fracturing approach, a coplanar jetting tool (Fig. 3) is preferred. The tool shown in Fig. 3 was designed for creating fractures perpendicular to the wellbore; however, other angles are possible, including fractures that are parallel to the wellbore axis. The annulus is pressurized to a level close to the fracturing pressure, and the jetting tool is generally pressured at a 4,000- to 5,000-psi differential pressure. These combined pressures allow large hydraulic fractures to develop while the acid etches the fracture surface.

A new process, used here for the first time, is a variation of the hydrajet fracturing technique. This process involves squeezing acid using a jetting tool (shown in Fig. 4) or a slowly rotating hydrablast tool (**Fig. 6**). During this process, the annulus is subjected to a pressure higher than the formation pore pressure (pressure gradient of approximately 0.5 psi/ft) while acid is jetted at a relatively high pressure. Because this annular pressure is well below the fracture gradient, hydraulic fractures may or may not be created unless the distance between the jets and the wellbore wall approaches zero.

Treatment Success

Successful well treatments depend on identifying the causes of the production deficiency for the specific well to be treated. Descriptions of various production deficiencies and treatment options follow:

- **Debris.** If the production problem is caused by debris plugging along the wellbore, the well can be cleaned with an effective hydrablasting and cleaning service. This service addresses the problems associated with cleaning sand and debris from large-diameter, deviated, or horizontal wellbores. Using CT with standard industry practices can yield poor results. This service combines design software, specialized fluid systems, and a wash tool designed for the different mechanics associated with deviated and horizontal wells.
- **Filter Cake and/or Near-Wellbore Damage.** If near-wellbore damage is causing the production deficiency, an acid wash might be the best solution.

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- **Deep Damage Close to the Wellbore.** If deep damage close to the wellbore is decreasing production, an operator can place several small fractures to bypass the damage. This option may also be applicable for near-wellbore damage because small fractures increase the effective wellbore diameter.
- **Wellbore Location.** If the wellbore is located in a poorly producing zone in the reservoir some distance from a better interval in the reservoir, or if a vertical permeability barrier exists, the operator may need to create larger fractures that can communicate the wellbore with more productive zones.
- **Low Formation Permeability.** If the average permeability of the formation is too low to produce at commercial levels, placing numerous hydraulic fractures (proppant fractures or fracture acidized) is the only viable method for effective production stimulation.

Of course, successful treatments must improve production at the lowest possible cost. Therefore, engineers must consider economics (cost/benefit ratio) when choosing a production-enhancement solution.

Case Histories

Formation Properties. The formation properties of the wells stimulated in these case histories differ. The area of the formation containing Wells C and D has higher porosity and less fracturing than the rest of the wells. In these wells, fracturing exists in a number of selectable areas of the wellbore, and, consequently, the hydrajet fracturing technique was used to concentrate on these specific areas. Wells A, B, E, F, and G are located in an area of the formation that has lower porosity, lower effective permeability, and fracturing throughout the wellbore. This necessitated a stimulation procedure that would not concentrate on specific areas of the wellbore but would still use the effective downhole mixing and high-pressure jetting associated with the hydrajet stimulation system.

General Procedures. The general procedure for stimulating newly completed wells in this area involves using N_2, which lightens the hydrostatic column, to unload the drilling fluids from the wellbore. The well is then allowed to flow until it achieves a semi-stabilized, prestimulation rate and pressure. Next, several acid washes are performed with the hydrajet tool while the well is flowing to flare. This process removes excess filter cake or superficial drilling damage in the wellbore. The well is flowed again, allowing operators to determine the effectiveness of the wash. Finally, a hydrajet squeeze stimulation is performed over the entire openhole section. Acid containing inhibitors and foaming agents is pumped though the CT at high rates, and CO_2 is pumped down the annulus. The well is then unloaded and allowed to flow until cleanup and an evaluation of the effectiveness of the stimulation treatment are completed.

After the wash was performed in Well A, the operator decided that a squeeze was not necessary. However, Well A may have achieved a significantly higher production rate if it had been subjected to a hydrajet squeeze stimulation.

Table 1 presents a summary of the case histories. This table shows the treatments and general stimulation results.

Overview of Well Treatments. Conventional acid washes were performed in the first and second wells (Wells A and B), but the second well (Well B) was also squeezed with acid. Well C was hydrajet fracture-acidized through coiled tubing in an attempt to place several small fractures along the open hole. The fourth well was also hydrajet fracture-acidized through CT, but downhole mixing procedures used during this treatment provided in-situ generation of carbon dioxide (CO_2) foam. Fewer yet larger fractures were placed in this well. A slowly rotating jetting tool was used to treat the fifth well, while a simple, high-pressure drop nozzle was used to simultaneously mix acid with CO_2 and N_2 downhole in the sixth and seventh. Achieving sufficient bottomhole and tubing pressures may have allowed the creation of many small, near-wellbore fractures in these wells. (Detailed job information for each of these seven wells is provided later in this section).

Well A. Well A, an openhole horizontal well, is the best potential producer well within the case-study group. It is approximately 12,500 ft deep and includes a horizontal openhole section extending approximately 2,200 ft. Production from Well A before the stimulation treatment was 10.6 Mmscfd at a pressure of 2,175 psi. The reservoir pressure is approximately 4,500 psig, and porosity is approximately 5%.

Before the hydrajet stimulation technique was invented, operators performed simple acid washes to improve production. The treatment consisted of 13,000 gal of 15% HCl. After three such treatment passes, production increased to 25 Mmcfd at a pressure of 2,500 psi (**Fig. 7**). This increase, when normalized with Fetkovich's backpressure correction equation[12] equates to an increase of 253%.

Well B. Well B is also a horizontal well with a depth similar to that of Well A and a horizontal openhole section extending approximately 2,200 ft. Initial production from this well was 2.5 Mmscfd at a pressure of 360 psi with a reservoir pressure of approximately 4,650 psi and a porosity of 5%.

The operator performed a conventional acid wash/squeeze with two passes of an acid wash consisting of 8,300 gal of 15% HCl. Production increased to 3.3 Mmscfd (a 32% increase). A second treatment was performed with an additional 13,500 gal of 15% HCl foamed with nitrogen and squeezed into the matrix in two passes. This treatment increased production an additional 156% to 8.47 Mmscfd. However, over a 30-day period, the production decreased to 3.7 Mmscfd, indicating that the treatments did not reach the natural fracture network and that larger fractures might be necessary.

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