Originally appeared in World Oil® NOVEMBER 2012 issue, pgs 37-44. Posted with permission.

Fiber-laden diverter system improves stimulation economics, enhances well performance

Use of a new diverter in Saudi Arabia has greatly impacted engineering practices and enabled treatment volumes optimization. The system lowers total diverter and acid usage per net pay, achieving consistent post-stimulation production performance.

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While advanced stimulation techniques are not new in Saudi Arabia, where most current gas production comes from carbonate reservoirs in the eastern part of the country, a novel fiber-laden self-diverting acid system is increasing well productivity almost threefold in some wells. The fluid achieves a balance between induced temporary fracture damage and conductivity.

Acid fracturing treatment performance is largely determined by the achieved effective etched fracture length. Evolution of fracture length during such treatments leads the acid leakoff rate to increase progressively up to a point when the fracture stops extending. Therefore, zonal coverage and fluid loss control in naturally fractured carbonate reservoirs with high permeability contrast are the key challenges during acid fracture treatment.

Nonreactive and reactive polymer-based fracturing fluids and diverters were historically accepted as systems that could efficiently control fluid leakoff. However, the performance of such fluids relies on wall-building fluid loss additives (such as polymers). Filter cake on the etched fracture wall can cause skin. While non-degradable particulate fluid loss additives can be a good leakoff-control tool, the particulates could permanently shut off natural fractures and stop their production contributions.

Recent advances in stimulation fluids and diverter technologies have given Saudi Aramco engineers the ability to further improve post-stimulation well performance while simultaneously enhancing treatment economics. This task has become more difficult as the ongoing gas development targets tighter zones that require maximum reservoir contact and effective stimulation to achieve production goals. The heterogeneous nature of the reservoir has increased the need to closely monitor treatment parameters and reservoir response, and make adjustments onsite and in real time. Therefore, an efficient and adjustable strategy, designed to minimize diversion efficiency in zones with low permeability contrast and maximize it in those with high contrast, has become a necessity in the quest for successful stimulation.

The challenge is to find the right balance between induced fracture damage and conductivity. A new fiber-laden fluid, now being introduced in Saudi Arabia, is designed to temporarily decrease or block fluid leakoff into natural fractures and wormholes in carbonate reservoirs by creating bridges with fibers, and increasing viscosity as the acid spends.

Fig. 1. An example of carbonate rock outcrop heterogeneity, left. Because carbonates are biological deposits, pores have highly complex shapes and sizes. (Photo courtesy of Mohammad Reza Saberi, University of Bergen). Khuff main lithofacies and gamma ray correlation are shown, right. Reservoir properties vary significantly in this Permian Khuff formation with colossal dimensions. (Courtesy of Saudi Aramco)

Proving ground for stimulation fluids. The Saudi Arabian reservoirs, specifically the Khuff formation in Ghawar field, are heterogeneous, with variations in permeability and porosity, and a formation composition comprised mainly of calcite and dolomite interbedded with streaks of anhydrites, which act as nonproducing sections and possible barriers. Pressure, temperature and gas composition in these reservoirs vary significantly throughout the field at different depths. Unlike sandstones, the heterogeneous pore systems of carbonate rocks defy routine petrophysical analysis. Because carbonates are deposited through biological activity, the pores have highly complex shapes and sizes, **Fig. 1.**

From simple acid washes to major acid fracturing operations, every carbonate stimulation technology has found an application over the years in these reservoirs. Rigorous evaluation ensured that only the most useful technologies survived the test of time.

With a large number of high-volume acid treatments performed in the past decade, both Saudi Aramco and service providers have gained significant knowledge in this type of major stimulation operation and have consistently introduced optimization steps. The majority of the acid fracturing treatments targeted the multilayered carbonate formations that are interbedded with impermeable layers separating the net pay. Significant heterogeneities in stress profile and reservoir quality are present throughout the field, which combined with the deep and hot nature of the reservoir, has made achieving uniform, effective stimulation of all targeted layers in these wells a challenging task.

Treatment designs comprising alternating stages of polymer pad, diesel emulsified acid for deeper penetration and in-situ gelled acid, and a polymer-based system for diversion and leakoff control, have been extensively used in most of the fracturing treatments. In an attempt to control excessive progressive leakoff during the treatment, degradable fibers were added to the crosslinked polymer pad stages. These particulates, helped reduce leakoff by bridging wormholes and natural fractures, thereby allowing acid entry into targeted stimulation zones.

Field implementation results showed significant treatment design and cost optimization, leading to improved gas production performance. However, the bottomhole treating pressure (BHTP) could not be maintained above the fracturing pressure limit throughout the duration of the treatment, which suggested that the created fracture closed during the treatment, and that the desired fracture geometry was not ultimately achieved.

Treatment design optimization. Acid fracturing treatment designs in these carbonate reservoirs have evolved in parallel with advances in stimulation fluids and technologies. The most common is alternating stages of viscous nonreactive pad fluid with stages of acid, which is designed to limit wormhole growth once it begins. The first pad stage pumped initiates the fracture geometry, followed by the first acid stage, which etches a portion of the fracture and creates significant wormholing—resulting in high fluid leakoff that must be controlled.

The second pad stage then fills up the wormhole network, and prevents the second acid stage from entering the established network. This process is repeated until the designed treatment volumes are placed into the formation. The higher the viscosity of the nonreactive pad fluid, the more difficult it is for acid to displace the gelled fluid and restart wormhole growth. This technique also implicitly employs viscous fingering as a secondary deep penetration mechanism; therefore, the primary intent is to increase hydraulic fracture width and to provide acid leakoff control.

Several techniques to achieve effective acid leakoff control and diversion have been used by Saudi Aramco throughout the gas development program. Nonreactive and reactive polymer-based fracturing fluids and diverters were used first, followed by polymer-based self-diverting acid systems, and more recently by polymer-free viscoelastic acid systems. Significant optimization steps, derived from field experience and post-stimulation results, have also been consistently applied, leading to a reduction of up to 70% of the initial pad volume being implemented without negatively impacting fracture requirements and performance while still reducing pumping time and fluid costs.

Use of associative polymers showed diversion improvement, but the BHTP could not be maintained above fracturing pressure throughout the whole treatment, so the practice was discontinued. The relatively recent use of viscoelastic surfactant-based diverter technology, along with degradable fibers for leakoff control, has significantly improved post-treatment performance.

Combining the best carbonate stimulation techniques. The Schlumberger MaxCO_3 self-diverting acid system, combining degradable fiber and a polymer-free viscoelastic diverting acid (VDA), was first tested in a number of matrix acid stimulation treatments, all of which yielded excellent results. The next logical application step is the transfer of lessons learned from the field trials to acid fracturing treatments. In the new system, the combination of the self-diverting acid and fiber enhances the diversion process by combining the aspects of both particulate and viscosity-based diversion techniques.

The acid system temporarily blocks or decreases leakoff into natural fractures and wormholes creating fiber bridges in the perforation tunnels or in fractures and by increasing viscosity as the acid spends. The VDA component of acid is based on the J557 viscoelastic chemical system, an innovative system that provides more uniform stimulation of carbonate formations. Following treatment, the chemical system is cleaned up in the presence of produced hydrocarbons or formation water.

The VDA component of the system is a surfactant mixed with HCl and standard acid additives, such as inhibitors, iron control agents and non-emulsifying agents. It can be pumped as a single stimulation fluid or as a diversion stage during acid treatments. A main feature of the surfactant is that it gains viscosity as it spends. During the reaction of HCl with limestone, calcium chloride is produced. The calcium chloride reacts with the surfactant to form long, worm-like or rod-like micelles. These micelles temporarily plug the wormholes and fissures in the formation, directing fresh acid to lower permeability areas not stimulated.

The acid system also has a fiber component, J595. It is a low-density, nontoxic synthetic fiber that is compatible with many fluid systems designed to increase the diversion ability of self-diverting systems in natural fractures, where viscous leakoff alone is not effective. J595 generates a fibrous network that bridges across fissures and dominant wormholes, creating flow restrictions. Following stimulation, the fibers degrade into an organic acid that is readily produced from the formation.

After the stimulation treatment and during the well shut-in period, the base fluid system breaks either by contact with hydrocarbons in the reservoir or with pre-flush or overflush fluids mixed with a mutual solvent. The fibrous component, which degrades with temperature and time, requires a small amount of water supplied by the base fluid to degrade completely. As the material degrades and hydrolyzes, it creates a weak acid that continues to stimulate the formation. The soluble byproducts, reduced to a size that does not impair flowrate, then flow back and can be handled at the surface using conventional techniques while the undamaged stimulated reservoir is producing.

In comparison tests of "wall-building" capability performed during the development phase, two polymer-free systems were pumped through a 0.078-in.-wide nonreactive slot, imitating a natural fracture. After some initial spurt loss, the new fluid system was capable of building a "fiber cake" at the entrance of the slot, Fig. 2. The non-fiber-laden viscoelastic diverting acid in this test leaked through the slot opening at a constant rate throughout much of the experiment, and never demonstrated a wall-building phase.

The system's unique chemistry offers the ability to adjust the degree of diversion throughout the treatment and another benefit is faster well cleanup. Due to the high efficiency of the system, less fluid volume is loaded into the formation during the acid fracturing treatments. Flowback statistics indicate that the clean-up period drops from an average of 4.7 days to not more than two days.

First applications in Ghawar field. A significant number of wells in Ghawar field were stimulated with the new fluid system, covering a wide range of single and multi-stage matrix acidizing and acid fracturing treatments. Well X and Well Y were selected for illustrative purposes of how the new acid system performed. Well X was chosen, because actual downhole pressure data was collected from it during an acid treatment, and the effect of the self-diverting acid system can be clearly observed. Well Y was chosen, because it exemplifies the reservoir characteristics and post-stimulation results achieved in the majority of wells treated with the new acid system.

Well X, an open-hole horizontal gas producer equipped with a multistage fracturing completion designed for three acid fracturing treatments, was drilled in a tight-gas carbonate reservoir to a TVD of 17,010 ft and fitted with a completion designed for acid fracturing stages in three sections isolated mechanically by openhole packers. The toe section, the tightest zone, had 379 ft of reservoir contact and was the first of three acid stages.

Prior to the treatment, gauge hangers with bottomhole gauges were set to record bottomhole pressure and temperature during treatments. An injectivity test was performed ahead of the main acid job to calibrate treatment parameters, Fig. 3.

The first acid fracture treatment stage was successfully performed by the treatment schedule into the formation at a maximum treating surface pressure of 11,625 psi and a rate of 30 bbl/min. Degradable fiber was dynamically adjusted during treatment, and fiber concentration ranged from 75 lb/1,000 gal to 100 lb/1,000 gal in the final diverter stage. At the end of the acid fracturing treatment, a relatively small acidizing stage was pumped to

Fig. 2. Laboratory test results showing the "wall building" capability of the new fiber-laden fluid system as compared to two polymer-free systems. The non-fiber-laden fluid leaked through the slot opening at a constant rate.

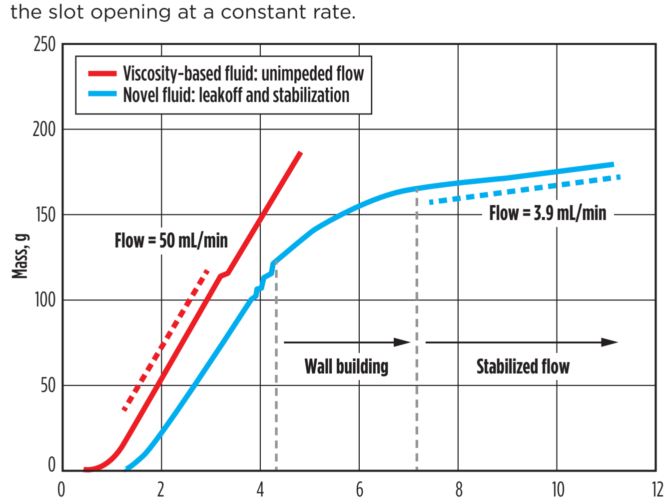


Fig. 3. MiniFrac test data analysis for Well X. The first stage was successful at 11,625 psi and a rate of 30bbl/min. Fiber was adjusted dynamically during treatment. At the end of the treatment, a closed fracture acidizing stage was pumped to maximize conductivity in the near wellbore area.

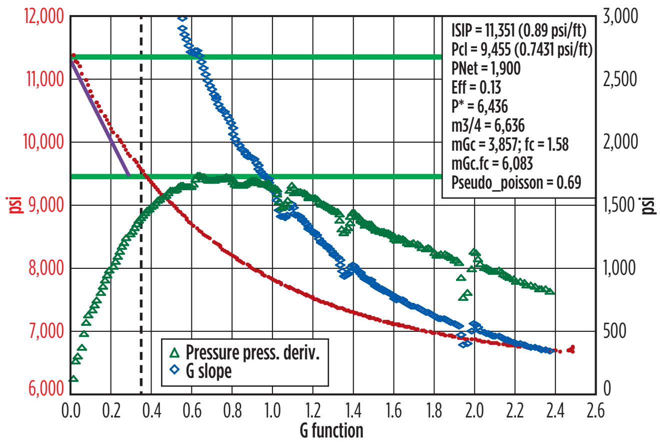


Fig. 4. Nodal analysis performance curve for Well X. Using the modified gray tubing correlation, a nodal analysis model was built to match the well performance and normalized to a representative FWHP of 1,400 psi.

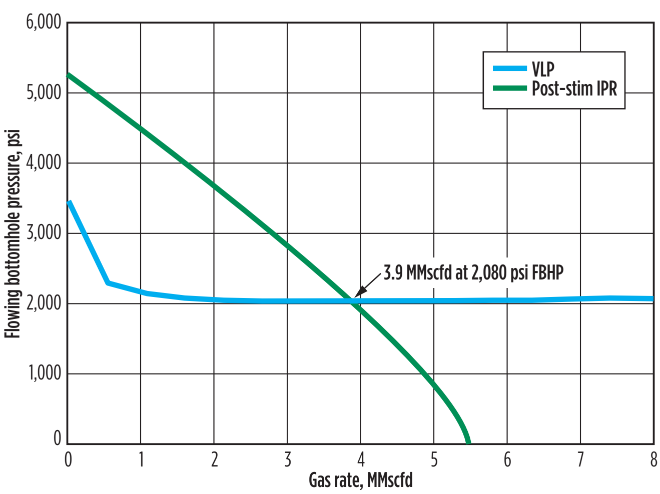


Fig. 5. Estimated productivity index for Well X. Results from nodal and productivity index analyses clearly showed that the Stage 1 stimulation treatment was successful and achieved excellent, better-than-expected results.

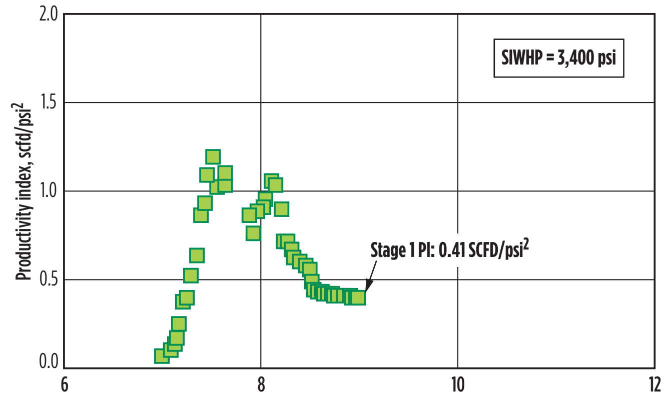
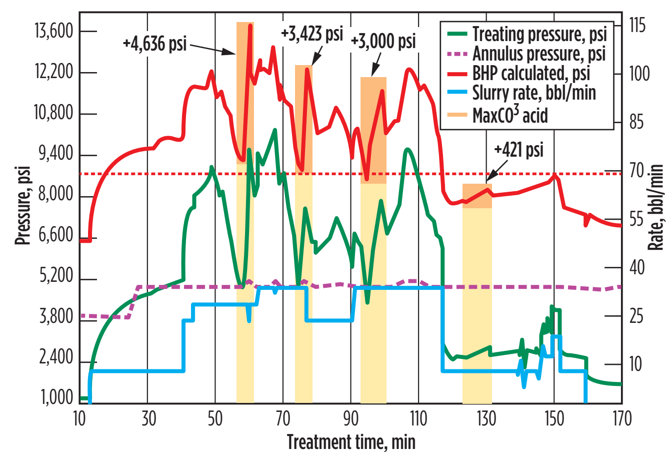


Fig. 6. Actual pressure and temperature data during acid fracture treatment in Well Y. By dynamically adjusting degradable fiber concentration during the final treatment stages, the BHTP was maintained above the fracturing pressure.



maximize conductivity in the near-wellbore area.

The stimulation treatment was performed as per design, maintaining BHTP above fracturing pressure during the entire treatment. The bottomhole gauge reading showed substantial BHTP increase, when the fiber-laden diverter stages entered the formation, indicating effective fluid diversion even in the long openhole interval.

A nodal analysis model, using the tight reservoir characteristics in the area, was built to match the well performance, using the modified gray tubing correlation, and normalized to a representative flowing wellhead pressure (FWHP)of 1,400 psi, Fig. 4. The productivity index for the well was also calculated, Fig. 5. Results from these analyses clearly showed that the stage-one stimulation treatment was successful and achieved excellent, better-than-expected results from this tight section of the well.

Well Y, a highly slanted well with a 65° inclination, demonstrated record-breaking BHP gains (an increase of more than 4,500 psi), as the new acid system came in contact with the formation, indicating excellent leakoff control and diversion performance. Also, the BHTP was maintained above the fracturing pressure throughout the treatment, Fig. 6.

The well flowed at a post-stimulation rate of 23 MMscfd with a FWHP of 2,230 psi, compared with a pre-stimulation rate of 8 MMscfd with a FWHP of 2,060 psi, an almost threefold increase.

More uniform stimulation of Saudi's carbonate formations and reservoirs with high-permeability contrast has been witnessed in more than 50 wells stimulated with the new system. This technology has become routine, based on the excellent results achieved since the start of system implementation. WO

ACKNOWLEDGEMENT

This article was prepared from SPE-SAS-512, presented at the 2012 SPE Saudi Arabia Section Technical Symposium and Exhibition in Al Khobar, Saudi Arabia, April 8–11, 2012; and SPE 142512, presented at the Middle East Oil & Gas Show and Conference in Manama, Bahrain, March 20–23, 2011. The authors thank Saudi Aramco and Schlumberger for permission to publish this work.

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