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Conventional diverting techniques and novel fibrer-assisted self-diverting system in carbonate reservoir acidizing with successful case studies

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ABSTRACT

Conventional diverting techniques may not be useful, and the use of the advanced and well-documented diverting technique is needed to overcome the complexity and heterogeneity of carbonate reservoirs. Nowadays, there have been a lot of materials and techniques utilized for acid diversion. This paper aimed to consider various utilization of fiber-assisted self as the diverting system in acidifying carbonate reservoirs. One of the main reasons for its ability to overcome uncertainty is that the fiber itself is an inherent property, allowing for an automatic diversion adjustment downhole. When a media with infinite permeability, such as a perforation tunnel or natural fracture, is filled and bridged with a material of finite permeability such as degradable fiber, this creates a temporary skin to injectivity in that zone. This is a powerful concept, as it is a way, despite uncertainty from a lack of logging data or uncertainty in the data itself, of dampening the reservoir’s natural permeability contrast. It does not rely on petrophysical certainty to design a successful treatment.

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1. Introduction

Approximately two-thirds of the world’s oil reserves and vast gas reserves are carbonate reservoirs (Shokry and Tawfik 2010; Rabbani et al., 2018; Davarpanah and Mirshekari 2019a; Esfandyari et al., 2020b, c; Hu et al., 2020b). Carbonate minerals are relatively impermanent and frequently undergo numerous dissolution phases and recrystallization (Bukovac et al., 2012; Davarpanah et al., 2018a; Hu et al., 2020a). Due to the complex nature of these reservoirs, reservoir characterization often leaves many uncertainties. Thus, finding the proper harmony between risks connected with these unknown conditions and optimized stimulation makes these treatments more complicated (Davarpanah et al., 2018b; Nesic et al., 2020; Zhu et al., 2020). These purposes become very hard in positively declined, layered, and high permeable fractured reservoirs. High reservoir permeability contrast and non-uniformed damage propagation in objective zones cause stimulation fluids to take the least resistance path and preferentially enter the thief zones. Many methods have been developed to prevent acidizing fluids’ penetration to high-permeability formations and into low permeable parts to solve this issue. Diversion is achieved by mechanical or/and chemical means (Davarpanah and Mirshekari 2019c; Jin and Davarpanah 2020; Sun et al., 2020; Zhou and Davarpanah 2020). According to the mechanical diversion, the high permeable zone is blocked mechanically, and the fluid is forced to pass through a low permeable zone. The chemical deflector will be established during this process. Selecting the proper method depends on various parameters like applicability, accessibility, and associated costs. The applicability of a diverter mainly depends on the reservoir and well properties (Leal Jauregui Jairo et al., 2010; Davarpanah 2018a, 2019; Davarpanah et al., 2019a).

A review of diversion techniques shows that carbonate reservoir has undergone substantial change during stimulation ways, with an alteration away from conventional stimulation fluids toward non-damaging viscoelastic diverting acid systems (Asiri et al., 2013; Davarpanah 2018b, 2020; Mazarei et al., 2019; Esfandyari et al., 2020a). The new fiber-laden self-diverting agent mixes fiber and a viscoelastic diverting acid without polymer (Davarpanah and Mirshekari 2019b, 2020; Ebadati et al., 2019; Pan et al., 2020). It
is designed to temporarily block or reduce fluid leakage into fractures and microfractures in carbonate reservoirs using fibers and raising viscosity by viscoelastic diverting acid. The mixture of the fiber and self-diverting acid improves the diversion method by mixing particulate and viscosity-based diversion techniques. After injection, these systems break with different working, on contact with oil from the reservoir or with over-flushes including double-faced solvent. The attendance of a small quantity of water by the base fluid to decay entirely is essential in the fibrous component. As the fibrous material hydrolyzes and degrades, it constructs an acid that maintains stimulating the formation. The solvable byproducts then flow back at the surface using conventional methods, whereas the intact stimulated reservoir is exploiting.

This work investigates the significant role of acidizing and diversion, the types, goals, advantages, and drawbacks of the methods currently used in petroleum fields, and finds the best existing method for acidizing naturally fractured carbonate reservoirs.

2. Methodology

2.1. Thick and heterogeneous carbonate reservoir matrix acidizing

The main aim of well stimulation is to improve the oil and gas field’s economic condition through higher hydrocarbon delivery with inexpensive ways (Porges 2006). A study of reservoir characteristics and potential stimulation techniques before the field operation may enhance the treatment’s effectiveness. Low well productivity may result from natural reservoir limits or drilling-, completion-, and production-induced formation damage (Civan 2014). Depending on the nature of production impairment and the reservoir characteristics, several stimulation techniques have been practiced, including matrix acidizing (Kalfayan and Martin 2009), acid fracturing (Whisonant and Hall 1997), hydraulic fracturing (Rahim et al., 2002; Davarpanah et al., 2019b), completion (Babadagli 2007), fracpack (Brown et al., 1996), as well as other treatments (Sinson et al., 1998). Successful well stimulation is possible through an optimized well stimulation workflow comprising five stages: reservoir and geological description, completion strategy, stimulation plan, performance, and productivity modeling (Fig. 1). Each stage should be addressed to maximize the stimulation benefits (Abou-Sayed et al., 2007).

One of the routine stimulation jobs in carbonate reservoirs is matrix acidizing (regularly HCl: 15–28 wt %) to raise the permeability near-wellbore by making wormholes with acid dissolution (Crowe et al., 1992). In heterogeneous formation, the significant reservoir permeability contrast and non-uniform damage distribution in aimed zones are two crucial factors that affect simulation results. Stimulation fluid tends to take the path of minimum resistance and preferentially to enter the thief zones. Furthermore, variable reservoir pressures and the perforated interval in thick carbonate reservoirs further exacerbate the problem. Inappropriate diversion results in the undisturbed zones are over-stimulated, permitting them to dominate post-treatment production. Besides, the adjacent lower-quality zones unstimulated, hindering them from reaching the highest potential. This may not affect the well or field’s initial production, especially in gas wells that are not produced to their maximum potential. However, there can be significant consequences to the field’s long-term production and recovery (Shuchart et al 2010). To achieve full zonal coverage and optimal placement with matrix acidizing in thick and heterogeneous carbonate reservoirs, comprehensive data gathering to minimize the uncertainties and risks in the stimulation and use of advanced diversion methods is required.

2.2. Acid placement and diversion in the wellbore — matrix acid treatments

The best way to ensure that a suitable placement has occurred in matrix acidizing is diversion techniques. By Darcy’s equation, the intervening zone coverage is evaluated by matrix acidizing. The changeable parameters that can be controlled are (Kalfayan and Martin 2009):

1. The rising injection rate (Q)
2. Holding the maximum injection pressure differential (ΔP);
3. The increasing of acid viscosity (μ);
4. Isolating the targeted damaged or low permeable zone (h);

Fig. 1. Carbonate matrix simulation workflow.
(5) Make temporary local skin in high permeable zones (S).

The diversion techniques that have been used (individually or in combination) to matrix acidize thick carbonate reservoirs include the following (Retnanto et al., 2012):

(1) Multiple and independent staging approach;
(2) Multistage approach (with non-independent stages);
(3) Limited-entry perforating;
(4) High-rate pumping;
(5) Coiled tubing conveyed treatments;
(6) Ball sealers;
(7) Chemical diverters.

2.3. Independent, multistage approach

There is no doubt that mechanical techniques are the surest method for fluid placement in areas where they would not naturally travel. If fluid travel is stopped in low permeable zones, it will have no remedy to it. For existing well, mechanical diversions such as straddle packers may encounter several problems, such as fluid communication issues. Another main concern of the mechanical diversion is the total interval length related to the rig time available. This technique may be suitable for the exploration well with several short test intervals and techniques usually combined with other techniques, such as chemical diverters (Entchev et al., 2012). These procedures are so over-priced and thus are less preferable in general (Malik et al., 2016). Fig. 2 shows the schematic of mechanical diversion by utilizing a straddle packer in a perforated cased hole.

2.4. Multistage approach (with non-independent stages)

A multistage approach without an independent stage is performed involving the perforation strategy and stimulation strategy at the same time. The permeability range classifies the long thick carbonate reservoirs. The lowest permeability formation will be perforated and stimulated first before the higher permeability range. The stimulation treatment is then applied to all intervals simultaneously. The advantage of this approach is a controlled stimulation treatment on the low permeability intervals. The initial perforation planning is highly dependent on the well deviation and wormhole profile. Perforation a few feet from a high permeable layer can extend into the high permeable layer (Fig. 3). The reliable results of applying the multistage approach convinced the ExxonMobil and RasGas Companies engineers to change the previous completion (single stimulation design (K1–K4 layer) or “cookie-cutter”) to multistage completion and stimulation strategy (K1–K3 and K4 separately) in the North Field in Qatar (Cohen et al., 2010).

2.5. Limited entry

The limited entry has been used to stimulate thick carbonates through the use of low-shot density perforating. Created back pressure increases the wellbore pressure and forces stimulation
liquids into zones with lower permeability. By combining limited entry with chemical diverters, powerful diversion can be obtained. A key drawback of limited entry, especially with high rate gas wells, is the additional completion skin and its effect on required drawdown pressure (Jamali et al., 2017).

2.6. High pumping rate

As can be known, the first influential factor for placement in matrix treatment is rate — which is the foundation of the maximum pressure differential and injection rate (MAPDIR) method. This process has existed for a long time, but still, it has a low value. In the MAPDIR technique, the acid is pumped at the highest rate and under fracturing pressure. According to this assumption, diversion’s necessity is markedly diminished by retaining the highest permissible injection pressure. The concept is also intrinsic to the limited entry concept. Conversely, instead of reducing the perforation shot density, the flow rate can be increased, which will create the same effect. The pumping rate is limited by completion size and surface pressure limits, and bottom hole pressure limitations can involve both packer limitations and the fracture gradient (Paccaloni 1995).

2.7. Coiled tubing

Coiled tubing (CT) (Fig. 4) is one of the essential instruments in acid placement. It is more beneficial than the common bull heading treatments during a matrix acidizing and is often used as a conveyance method for the stimulation treatment, especially in a horizontal well.

The essential advantages of coiled tubing in acidizing are:

1. CT string volume is small, and fluid can be swiftly moved;
2. With nitrogen injection, easy treatment displacement can be attained;
3. By attachment nozzles, the treatment of intervals might be accomplished;
4. Prevents the corrosive fluid to contact with the entire strings.

Disadvantages include: pump rate limitations (higher friction pressures), solids such as ball sealers are challenging to put using CT, acid combinations must be entirely mixed firstly, and during injection, small pits into the string can rapidly lead to tubing failure and fishing tools. Generally, acidizing with coiled tubing is more successful than bull-heading, but bull heading has better results in some fields. Mitchell et al. (2003) depicted that acid placement with coiled tubing was obviously better than simple bull-heading, and generally, this is a considerable way to treat. Acidizing treatment in one field of Kazakhstan shows that an increase in productivity index with bullheaded viscoelastic acid is higher than coiled tubing conveyed viscoelastic acid. This result shows that there is no guarantee that the acid flow penetrates peculiar zones (Mitchell et al., 2003; Bitanov et al., 2007). CT is very impressive in acidizing, particularly during smaller and horizontal areas treatment for wellbore damage zones by jetting the acid across the open-hole interval. Acidizing is a vertical well also might be done via CT fitted with a monitored jetting/rotating nozzle, which is counteracted across the treatment zone. This technique can decrease the acid volume during acidizing; besides, it can opt for a proper intervening treatment zone (Stanley et al., 2000).

2.8. Ball sealers

The first time that ball seals were used dating back to 1956 (Brown et al., 1963; Harrison 1972). Perforation ball sealers are likely the most widely used mechanical diversion method in perforated wells. The balls are usually used as an additive material to the acid and injected into the perforation. Two kinds of modern ball sealers are rubber or biopolymer. Fig. 5 illustrates how ball sealers divert the acid in targeted zoned by selectively blocking perforations in high permeable intervals.

The idea is that the ball follows the fluid’s flow path, including its entry into the perforation. The ball’s size is larger than the perforation, so it will block the opening seal fluid entrance until the wellbore pressure is more than the perforation pressure. As a rule of thumb, ball sealers must be 1.25 times the perforation diameter, and the ball sealer diameter should be one-third of the string diameter. When the treatment is achieved, the pressure is cut off immediately at the surface to “surge” the balls from the perforations. Ball sealers are most effective in the new wells with a low-density perforation (maximum of 4 shots per foot), especially in smooth and symmetrical perforations. Besides, they are suitable in the well-cemented casing with no vertical channeling. Ball sealers
are not useful in the horizontal perforated well because the perforations along the top of the pipe are intricate in seating the balls. Although they provide a powerful and easy way to promote diversion, they have considerable downside risk. It is common for the balls not to seal correctly. Moreover, there can be the ball sealers’ risk of not flowing back or damaging surface equipment.

3. Chemical diverters

Chemical diversion can be achieved by using the fluid that provides a temporary barrier to the diverted formation and alters the stimulation fluid’s direction to the desired ones. The main advantage of the chemical diverters approach is a single package of pumping service without mechanical diversions, such as packers, to be run in the well. Rig-less stimulation treatments take this approach as the best solution as no longer rig required running the mechanical zonal isolation. This chemical diversion system’s main drawback is the extreme permeability difference in natural fractures, fissures, and faults. Another drawback for the chemical diverters is the water zone. Another drawback for the chemical diverters is the water zone. In this case, improper design of the chemical diverter will lead to stimulation against the water zone. Based on the mechanism of viscosity generation, chemical diverting agent divided into the following group:

1. Foam;
2. Particulate (salt granules, benzoic acid, waxes, oil-soluble resin, gilsonite, and fiber);
3. Viscous diverter (emulsified acid, gelled acid, in situ gelled (Polymer and VES)).

3.1. Foams

Foam is a two-phase gas system (typically \( \text{N}_2 \)) as a discontinuous phase and liquid as a wetting phase in the presence of surfactant to maintain a stable two-phase. A high quantity of gas in
Fig. 11. Pressure-versus-time plot from a slot-flow experiment using fiber-laden VDA acid system (Asiri et al., 2013).

Table 1
Temporary skin to injectivity (Cohen et al., 2010).

| Reservoir permeability (mD) | Skin due to Fiber | Effective Perm due to Fiber (mD) |
|-----------------------------|-------------------|----------------------------------|
| 0.1                         | 0.077             | 0.1                              |
| 1                           | 0.47              | 0.9                              |
| 10                          | 3.3               | 6.8                              |
| 100                         | 19.4              | 26.5                             |
| 1000                        | 103               | 63.6                             |
| 10,000                      | 783               | 88.6                             |

Fig. 12. Wall building strength of the new fiber-laden fluid system (Leal Jauregui et al., 2010).
foam led to rising gas saturation and falling liquid saturation when it was injected into the rock near the wellbore. It decreases the relative fluid permeability of the zones where foam has infiltrated. The best temperature range and treatment interval in foam diversion is 150°C to 250°C and 50 to 500 ft, respectively. For longer intervals, because of the high friction pressure, pumping foam is so complicated, and therefore, CT is the best method for solving this problem. In gas reservoirs, the foam diversion is more suitable than oil and water reservoirs because cleaning is more natural in gas wells. Nevertheless, the foam diversion has some pitfalls, such as high pump friction pressure, more required facilities, and an increase in costs (Zerhboub et al., 1994; Parlar et al., 1995; Glasbergen et al., 2006; Gdanski and Lee 2007).

3.2. Particulate

3.2.1. Salt granules
While rock salt has relatively low solubility in strong acid, it is promptly soluble in water. The salt granules are usually mixed with other particulates, for instance, rock salt and benzoic acid flakes, rock salt, and wax balls to be more impressive as a diverting agent.

3.2.2. Benzoic acid
Nowadays, the most predominantly suitable particulate diverter is benzoic acid. It is used below 250°F (melting point.). The benzoic acid may be injected either in slugs or incessantly as an additive to acid mixtures. At higher pump rates, e.g., 2 to 5 barrels per minute, mixing continuously might be better. Benzoic acid may also be dissolved in water (as ammonium benzoate) and alcohol. When contacted by water at reservoir pH, benzoic acid in dissolved form in either aqueous or alcohol solution is precipitated as a smaller, softer, more easily deformed particle. Particle size can be controlled by adding a surfactant. The time necessary that one well to reach common productivity after acidizing with benzoic acid is six months because of its low solubility. The mixing of benzoic acid and rock salt in a 50/50 blend is useful diverting material. The best stage size is 0.25 to 2 lb. of sized diverting agent per gallon for acidizing for an extended interval. The benzoic acid flakes are brittle and break in surface equipment; therefore, selecting proper size distribution is difficult.

3.2.3. Waxes
Wax diverters are prepared in different forms (powders, granules, buttons, etc.). These materials are often eliminated from the well by the action of temperature and dissolution in liquid hydrocarbons. Different sorts of wax have melting points between 100 and 200°F. Deformable wax particles are well-known in this category and have the best efficiency in fractured and carbonate formations in the acidizing system, and is also being utilized in horizontal well stimulation.

3.2.4. Oil-soluble resins
Although oil-soluble resin diverters are not as conventional nowadays (because of a high melting point (300°F)) as they used to be, they still have an occasional application.

3.2.5. Gilsonite
Gilsonite is a hard, naturally-occurring asphalt material and has a melting point of 300°F. It is suitable for zones that produce liquid hydrocarbons.

3.2.6. Fibers
During these years, essential researches have been fulfilled using small fibers. Initially, it is utilized for preventing flow back additive, but it has depicted that they are strikingly efficient diverting agents in the matrix and fracture acidizing.

3.3. Viscous diverter

3.3.1. Emulsified acids
Acid is the inner phase, and hydrocarbon is the outer phase of
emulsified acid, and it results in diversion due to viscosity contrasts and enhances acid coverage of the wellbore. The reaction rate of emulsified acid is half of the typical acid. Therefore, it causes deeper acid penetration in the formation (Nasr-El-Din et al., 2001).

3.3.2. Gelled acids

A gelled acid is produced at the surface when gelling agents are added to acids to produce viscosified acid. Compared to the in-situ gelled acid, pumping pressure in this method is higher due to more pressure loss in the well column. Viscous diverters are useful for all kinds of wells. Gelled acids have excellent efficiency below 250 °F. In acidizing gas wells, gel damages the formations, and therefore, it is not a suitable selection in these cases.

3.3.3. In-situ gelled acids (polymers)

Polymer-based gels are a firmly established diversion technique. These systems use reversible, pH-triggered crosslinker additives to alter the fluid’s viscosity during the acid treatment. When combined with fresh acid, the polymer fluid has a low viscosity to facilitate pumping. However, once this acid becomes spent (At pH 2), the polymer crosslinks with Fe (III) or Zr (VI) and forms a gel, and the fluid viscosity increments (Fig. 6). The high gel viscosity blocks the flow of fresh acid into and out of the wormholes and swerves it into the low-permeability layers and, finally, to all the damaged zones. When the pH reaches 4, the viscous gel is beaked, and it can flow back quickly.

Polymer might contribute to residual formation damage. In reservoirs containing hydrogen sulfide (H2S) gas, the iron-based crosslinker might contribute to iron sulfide scaling in the reservoir, perforations, and the completion. Moreover, these purely chemical-based systems often rely entirely on viscosity to divert acid away from high permeable thief zones. Often, in wells with natural fractures, or faults, this diversion mechanism alone is not sufficient to effectively divert fluid away from these features (Haldar et al., 2004). The new fiber-laden self-diverting agent was developed to address the limitations of the mentioned diverters and improve matrix and fracture acid efficiency without any additional formation damage.

3.3.4. Viscoelastic surfactant

The potential risks of polymer-based stimulation fluids promoted researchers to find alternatives. Therefore, it led to exploring the polymer-free stimulating fluid named viscoelastic diverting agent (VDA). VDA fluid contains a viscoelastic surfactant (VES). VES surfactant is polymer-free and does not have detrimental impacts on formation. Besides, they reduce the pumping requirements and treat deeper layers. The surfactant molecule consists of a long-chain fatty acid, which is zwitterionic. During pumping down in well, VES is mixed with the acid solution and maintains low viscosity. As the acid is devoured by formation, the surfactant molecules start to aggregate into extended micelles and cause rising the fluid viscosity (Fig. 7). In addition to creating a diversion, higher viscosity decreases the rate at which the acid reacts with the formation, thereby allowing more time for the creation of deeper and more intricate wormholes.

While production starts, VDA fluid is contacted to hydrocarbons, which alters the environment’s ionic properties and causes the micelles to convert to spherical. When entanglement ceases, the micelles roam freely, and the fluid viscosity diminishes noticeably, enabling efficient post-stimulation cleanup (Fig. 8).

3.4. Success use of VDA in Saudi Arabia

There has been an essential change in carbonate reservoir stimulation techniques in Saudi Arabia, and VDA systems have replaced polymer-based stimulation. Before the appearance of VDA fluid, acidizing carbonate reservoirs in Saudi Arabia relied on crosslinked, gelled and emulsified acid systems. During a project, Saudi Aramco and Schlumberger find that the utilizing of VDA is much more impressive than simulation without the VDA systems. Fig. 9 compares the production rates of the five wells after stimulation with VDA fluid and the average production from 11 offset wells that had been stimulated without the VDA system.

3.5. Fiber laden viscoelastic diverting agent

During the past decades, a large proportion of lunched cases of diversion has been ineffective in this environment. Even with utilizing VDA fluids, engineers struggled to block the fractures and treat the formation’s remainder. In 2007, the Schlumberger Company began researching new fibers as fluid diverting additives. Success was achieved by a combination of fibers and VDA fluid (Asiri et al., 2013). This system is a mixture of degradable fibers and VDA fluid, as shown in Fig. 10. This new system can build bridges with the fibers and raise viscosity by acid consuming, and therefore, it causes to establish the interim block and reduce fluid leak into natural fracture and wormholes. The mixture of them improves the diversion by blending both particulate and viscosity-based diversion techniques (Bukovac et al., 2012).

The results of pressure evolution in laboratory-scale equipment followed a consistent pattern. Firstly, the pressure was constant. After a few seconds, the pressure increased noticeably when the fibers established a bridge and started to fill the aperture. Then, the cumulated inside the perforations and built a filter cake. As the viscous acid left the apparatus, the pumping pressure gradually decreased and eventually stabilized. Finally, the fibers hydrolyze and eliminate during a few days (Asiri et al., 2013) (Fig. 11).

Cohen et al. at (2010) mathematically showed that the magnitude of the skin was introduced in the system by this diversion method is proportional to the permeability of the formation. The most substantial impact is made on the most permeable zones with negligible effect on the least permeable zones (Table 1).

After acidizing, the base fluid is removed by various mechanisms, on contact with hydrocarbon from the reservoir or overflushes containing a mutual solvent. The fibrous component, which degrades as a function of temperature and time, requires a small amount of water supplied by the base fluid to degrade completely. Degradation and hydrolyze of fibers creates an acid that continues to stimulate the formation. Then the byproducts flow back to the surface using conventional methods (Cohen et al., 2010). The successful results of the laboratory study encourage engineers to field test this method. Recently, many heterogeneous carbonate reservoirs successfully and efficiently have been stimulated have the world worldwide (Qatar, Saudi Arabia, Brazil, Kazakhstan, Canada, and Kuwait).

4. Discussion

4.1. Optimizing production in Saudi Arabia

The Saudi Arabian reservoirs, specifically the Khuff Formation in the Ghawar field, are heterogeneous, with variations in permeability and porosity. The formation mineralogy comprises calcite and dolomite with a little anhydride, which behaves as possible barriers. Reservoir characteristics tremendously vary throughout the field at different depths. While sophisticated stimulation methods have existed in Saudi Arabia, a novel fiber-laden self-diverting acid is raising production approximately three times in some cases. MaxCO2 self-diverting acid system (diverting agent applied by Schumleberger), which combines degradable fiber and a
polymer-free VDA, was first utilized in some matrix acidizing; all of them had tremendous outcomes.

In comparison tests of “wall-building” capability performed during the development phase, two systems without polymer were injected in a 0.078-inch wide nonreactive fracture, imitating a natural fracture. After some surge loss, a “fiber cake” was built at the fracture entrance by new fluid, Fig. 12. Nevertheless, the VDA fluid without fibers leaked out via the fracture opening at an unchanged rate all over the test and never illustrated a wall-building phase (Leal Jauregui et al., 2010).

Bukovac et al. (2012) represented the post-stimulation production performance of five wells situated in the south of the Ghawar Field that was stimulated from 2007 to 2011. All five wells were targeting prolific Khuff-C carbonate reservoirs. These vertical wells were cased, cemented, and selectively perforated, targeting the streaks with high porosity, high calcite percentage exhibiting low stress. Later on, these wells were stimulated (acid fractured) using different types and volumes of diverters (conventional, conventional with low concentration fiber laden, and novel fiber laden diverter). The treatment designs were based on the acid fracturing technique where alternating phases of polymer-based fluid, emulsified acid, and diverter fluids were pumped into the formation to create a fracture pattern on the fracture face. Post-stimulation gas production in all five wells yielded good outcomes and attained the post-stimulation targets. The normalized value of reservoir quality (kh) was used to perform the comparative post-stimulation performance evaluation. Fig. 13 shows the performance of the polymer-free fiber-laden diverting agent in comparison with conventional methods.

4.2. Optimizing production in southern Mexico

The Jujo-Tecominoacan field is located in southern Mexico. The average depth of the production interval is 5000 m, and the reservoir temperature varies between 250 °F and 320 °F. This field has variable natural fracture density, and it causes a large permeability contrast between various intervals that can reach 1000:1 (Asiri et al., 2013). The drilling of one common well in 2005 has two different producing intervals: from 17,303 to 17,369 ft and 17,415 to 17,520 ft. The reservoir temperature and pressure are 279 °F and 3300 psi, respectively. The permeability contrast is 333:1. The initial production rate from 2006 to 2009 was 1278 bbl/d. Petroleos Mexicanos Company (PEMEX) performed several types of conventional with low concentration fiber laden, and novel fiber laden acid technology in thick, Middle East carbonate reservoirs. In: International Petroleum Technology Conference 2007, IPTC 2007.

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manage the significant uncertainty encountered when stimulating carbonates is through the fiber-laden viscoelastic diverting agent. The mixture of the self-diverting acid and fiber improves the diversion procedure by combining particulate and viscosity-based diversion. The carbonate reservoir acidizing has been improved nowadays, with a change from conventional stimulation fluids toward non-damaging VDA systems exactly in Middle-East. Production enhancement and operational efficiency of this diverter are well documented, but one less prominent but essential feature of this technique is its ability to give a robust performance with predictable results, despite the significant petrophysical uncertainty involved.

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