Acid Fracturing Optimizing Design and Application in Deep Naturally Fractured Carbonate

Mingguang Che1*, Yonghui Wang1, Jianxin Peng2, Changlin Zhou3, Kai Dong4,
1 Research Institute of Petroleum Exploration and Development, PetroChina, Beijing, 100083, China
2 Tarim Oilfield Co. Ltd, PetroChina, Kuerla, Xinjiang, 841000, China
3 XiNan Oil and Gas field Co. Ltd, PetroChina, Chengdu, Sichuan, 610041, China
4 CNPC Great Wall Drilling Engineering Co. Ltd, Beijing, 100101, China
*Corresponding author’s e-mail: chemg69@petrochina.com.cn

Abstract. More than 30% of carbonate reservoirs in the Tarim oilfield and XiNan oil-gas field are naturally fractured-vuggy reservoirs, of which the production is high in most cases and economic returns can be achieved within a short period of time. Acid fracturing is one of the key technology for development of such naturally fractured-vuggy reservoirs. Mud overflow and loss may be emerged at the same time while drilling fractured-vugular carbonate, once it happened, the well control will become complicated. So, the wellbore is drilled a certain distance up or transversal to these huge caves or natural fractures, and acid fracturing will be executed to connected the reservoirs to obtain the hydrocarbon in the reservoir. Acid-fracturing design of fractured-vugular carbonate is based on the relationship between the wellbore and fractured-vugular reservoirs. The acid fracturing design in naturally fractured-vuggy carbonate reservoir is different from the conventional one, it should be optimized based on the spatial positions of the fracture-vuggy body identified via geophysical prospecting, the wellbore and the distance between the two. In the case that the wellbore precisely reaches the top of the fracture-vuggy body, good oil and gas show or overflow is frequently happened. At this moment, drilling ceases and the wellbore are cemented and completed. The small-scale acid fracturing treatment is then carried out, and connectivity between etched fractures and the top of the fracture-vuggy body will lead to high hydrocarbon production. If a certain distance exists between the wellbore and fracture-vuggy reservoirs, 3D seismic imaging will be adopted to calculate the vertical distance between the center of the storage body and the wellbore, which is then used to optimize the injected fluid volume, pump rate and acid fracturing techniques. To create connectivity with the fracture-vuggy storage body relatively far away from the wellbore, acid fracturing involving preflush or multi-stage injection is used. Pressure drops by several ~ several tens of MPa usually occur as the artificial fracture propagates into the fracture-vuggy body. After fracturing penetrating into the fracture-vuggy body, acid injection starts. During the early acid injection, the pump rate is raised up for longer etched length inside the fracture. It is then lowered during the late acid injection to improve the conductivity of etched fractures. If multiple fracture-vuggy bodies exist near the wellbore, the temporary diverting acid-fracturing will be treated, optimized with respect to the distance between the wellbore and different fracture-vuggy storage bodies, spatial relationship between the maximum principal stress direction and fracture-vuggy storage body and the trend of natural fractures, will be implemented to communicate with multiple naturally fractured vuggy reservoirs. This acid fracturing integrating geophysical prospecting and wellbore trajectory has been applied in hundreds of wells in the Tarim oilfield. Moreover,
the success rate of such acid fracturing treatments is increasing with the advancement in the characterization of the fracture-vuggy reservoirs.

1. Introduction
Based on analyses upon geological characteristics, geophysical prospecting response, oil and gas shows in drilling and well logging results, the carbonate reservoirs in the Tarim oilfield can be divided into four types, as is presented in Table 1. The first type is the reservoir with large-scale natural fractures and vugs, which is formed in sedimentary faces like weathering crust, due to later diagnosis effects such as dissolution. This type of reservoirs is mainly characterized by its display of a string of beads in the vertical seismic profile, highly natural fractures and vugs, drilling gas blow off, severe lost circulation and overflow during drilling, and dissolution-induced large caves observed in imaging logging. However, owing to the strong heterogeneity of carbonate formations, fractures and vugs may not be presented in the wellbore data (of mud logging and well logging). The second type refers to the reservoir with dissolved pores and vugs. Such reservoirs are generally of reef-beach bodies, in which the storage space is the dissolved pores and vugs in the matrix. The main features of this kind of reservoirs are concluded as the a-string-of-beads-like or clutter display in the seismic profile, well-grown dissolved pores and vugs in core samples, relatively good show of oil and gas in drilling, and intensely dissolved pores and vugs detected by imaging logging. The third type is the naturally fractured reservoir, of which the features are the chaotic reflection display in the seismic profile, connected fracture networks shown in both core samples and imaging logging, and relatively good gas show in drilling. The last one is dominated by the matrix pore, and this kind of reservoirs is seen with no bead-like or chaotic display in the seismic profile. The matrix porosity and permeability are low, and the developed dissolved pore is mostly intragranular and unconnected. The core sample observation and imaging logging demonstrate no or poor natural fractures.

| Reservoir Type                             | Typical Core Sample | Geological Setting | Seismic Response | Oil & Gas Show                          | Imaging Logging                      |
|-------------------------------------------|---------------------|--------------------|------------------|-----------------------------------------|--------------------------------------|
| Highly fractured vuggy reservoirs         |                     | Weathering crust   | Strong seismic reflection shown as a string of beads | Drilling blow off, lost circulation, and overflow Fractures and vugs seen in core samples | Large dissolved holes observed |
| Reservoirs with dissolved pores and vugs  | Reef-beach bodies   | A-string-of-bead or chaotic reflections | Good oil and gas show; Highly dissolved pores in core samples | Dissolved pores and vugs observed |
| Naturally fractured reservoirs             | Near faults         | Clutter in the seismic display | Good oil and gas show; Highly natural fractures in core samples | Highly natural fractures |
| Reservoirs dominated by matrix pores      | /                   | N/A                | Poor oil and gas show; Tight core samples | No natural fracture or dissolved pore and vugs |

The acid fracturing technique for deep naturally fractured vuggy carbonate reservoirs presented in this paper is mainly applicable to the first type of carbonate reservoirs. Acid fracturing can be used for reservoir stimulation in the second and third types of reservoirs, and yet propped fracturing would lead to better long-term hydrocarbon production in such reservoirs.

2. Acid fracturing for fractured-vuggy carbonate reservoirs
The reservoir that produces a strong seismic reflection with a display of a string of beads in the seismic profile is the carbonate reservoir with highly natural fracture and caves. Due to the limited well trajectory
control and precision during drilling, the drill wellbore may to some extent deviate from the storage body of natural fractures and vugs. Taking the azimuth and distance of such deviations into consideration, this paper developed an acid fracturing technique integrating the geophysical prospecting, drilling and reservoir stimulation technologies.

2.1. The small-scale acid fracturing

In the case that the wellbore precisely reaches the top of the fracture-vug reservoir, generally good oil and gas show will be observed, or otherwise overflow and lost circulation may occur. Drilling should cease, and the wellbore should be completed. As is shown in Fig. 1, the reservoir is presented as a string of beads in the seismic display with strong reflection, and gas logging consistently detects gas, after the wellbore arrives at the top of the reservoir. Under such conditions, the small-scale acid fracturing is applicable, which can promote vertical connectivity, unchoking the flow path between the vug and wellbore and ultimately achieving high hydrocarbon production. If the gas content detected by the gas logging is high and, in the meantime, overflow or lost circulation occurs, acid fracturing, pumping 80 m$^3$ ~ 120 m$^3$ of gelled acid into the formation at the rate of 2 m$^3$/min ~ 3 m$^3$/min, is implemented, mainly to open natural fractures for oil and gas flow and improve the conductivity of etched fractures. When the detected high gas content is not accompanied by overflow or leakoff, the small-scale preflush-involved acid fracturing technology is applied, in which the pad fluid with 80 m$^3$ ~100 m$^3$ and 80 m$^3$ ~ 120 m$^3$ of acid are pumped at 3 m$^3$/min ~ 4 m$^3$/min and then the pump rate decreases to 1.5 m$^3$/min ~ 2.0 m$^3$ in the flush stage. The decline of the pump rate is to reduce the flow rate of acid through artificial or natural fractures, and therefore enhance the conductivity of etched fractures.

![Figure 1. The reflection characteristic displayed as a string of beads (left) and schematic diagram of acid fracturing promoting vertical reservoir connectivity (right)](image)

2.2. The deep-penetration acid fracturing

Reservoirs may present themselves as a string of beads in the seismic display with strong reflection, and yet no hydrocarbon or oil and gas show is detected during drilling through such reservoir areas. This may be explained by the errors of the well trajectory control or the limitation of the geophysical prospecting interpretation accuracy. In such cases, one should first calculate the vertical distance between the center of the fracture-vug storage body and the wellbore, on the basis of the actual well trajectory shown in Fig. 2. Then, the liquid volume, pump rate and pumping schedule of acid fracturing can be optimized with respect to the calculated distance. The adopted acid fracturing technology involves a large-scale pad and multi-stage injection of high vicious acid and gelled acid, or another combination of pad, multi-stage injection of high vicious acid and closed-fracture acidizing. The purpose is to create long acid-etched artificial fractures connecting the far field fracture-vug reservoir.
Figure 2. Wellbore near the favourable storage body (left) and how deep-penetration acid fracturing connects the wellbore with the reservoir (right).

2.3. The diverting acid fracturing
As illustrated in Fig. 3, the oil and gas show are weak, as the wellbore drilling through the vicinity of the reservoir zone displayed as a string of beads in the seismic profile with strong reflection. Moreover, the configuration of the in-situ stress field and natural fractures (or vugs) is unfavourable for the propagation direction of the artificial fractures, according to the well logging interpretation. Given the diverting acid fracturing technology is used, in which temporary plugging agents are injected during the treating of acid fracturing and force the artificial fractures to turn around and propagate towards the natural fractures and vugs. In terms of the use of the diverting acid fracturing, one should first calculate the difference between the two horizontal principal stresses, based on the well logging data. It is demonstrated by the well logging that the horizontal principal stress difference of the deep carbonate reservoir in the Tarim Basin is relatively small, ranging from 2 MPa to 5 MPa. This is desirable for the diversion of artificial fractures. With reference to the relative position of the favourable reservoir identified by geophysical prospecting against the well trajectory, the vertical distance between the center of the fracture-vug storage body and the wellbore is determined, which is then used to optimize the liquid volume, pump rate and temporary-diverting techniques.

The acid fracturing operation consists of injection of a large-scale pad fluid, temporary plugging, and injection of preflush fluids and acid. With a relatively small horizontal in-situ principal stress difference, diversion of artificial fractures will promote reservoir connectivity in multiple directions or expand the hydrocarbon drainage area of the reservoir.

Figure 3. Wellbore deviating from the naturally fractured vuggy reservoir, moreover, inconsistency between reservoir location and acid etched fracture propagating direction.
3. Applications

3.1. Application of the small-scale acid fracturing

The target interval of well A presents a strong bead-string type reflection in the seismic display, as is shown in Fig. 4. The estimated top of the vug is at 6385 m. The planar distribution prediction of the reservoir indicates that the band-like distribution of the reservoir covers a large area. Drilling gas blow off occurs at 6300.6 m, and so does well kick with an invaded volume of 0.3 m$^3$. The oil and gas show are relatively good, the total hydrocarbon content measured by gas logging is 68.69%. Drilling finishes earlier than planned, as good oil and gas show is observed. It is predicted that the base of the well section to be fractured should be the naturally fractured vuggy reservoir. Production testing is carried out prior to acid fracturing. With a 5-mm surface choke and tubing pressure of 36 MPa, the daily oil production amounts to 42.81 m$^3$, and the daily gas production reaches 98,607 m$^3$.

Figure 4. Vertical seismic profile of Well A (left), and planer distribution mapping of the reservoir (right)

The drilling blows off, overflow and results of gas logging indicate that the bottom of Well A is close to the top of the fracture-vug storage body, and the planar distribution prediction of the reservoir suggests that the wellbore is located within the band-like favourable reservoir. Thus, the small-scale acid fracturing treatment is implemented after completion, mainly to increase the connectivity between the wellbore and the near-by natural fractures.

The operating curve of acid fracturing in Well A is seen in Fig. 5. The pump rate is of 0.7 m$^3$/min ~ 2.6 m$^3$/min, and the operation pressure ranges from 8.2 MPa to 51.0 MPa. Totally 80 m$^3$ of gelled acid is injected into the formation. In the early stage of acid fracturing operation, the pump pressure gradually declines, as the acid is being injected into the wellbore and its higher density raises up the pressure of the liquid column in the wellbore. The acid penetrates the formation, after the operation pressure declines to 25 MPa. The pump rate climbs up to 2.6 m$^3$/min, after the operation pressure drops from 25 MPa to 12 MPa, and then the pressure maintains at about 20 MPa. Pumping ceases after 33 m$^3$ of the flush fluid is injected, and the shut-in pressure is 11.2 MPa. The tubing pressure remains the same during the measurement of the pressure drop. The injected acid has reached a relatively large fracture-vug reservoir. The pre-production is implemented with a 5-mm surface choke following the acid fracturing. The tubing pressure is 45.7 MPa, with daily oil production of 74.35 m$^3$ and daily gas production of 130921 m$^3$.

With the same pre-production scheme, the post-treatment daily oil production is 1.74 times of that prior to the treatment, while the daily gas production grows by 33% after the acid fracturing. The production stimulation is considerable.
3.2. Application of the deep-penetration acid fracturing

The target interval of Well B is in a favourable area with natural fractures and vugs, which is characterized by strong reflection in the seismic display. The treated well section from 6125 m to 6138 m produces good gas logging results during drilling, with a maximum total hydrocarbon content of 99.89%. The imaging logging indicates relatively good pores and vugs, and the reservoir is classified as the naturally fractured vuggy reservoir. As is shown in Fig. 6, the planar distribution prediction of the reservoir illustrates that Well B lies within the favourable storage body in a distance of about 110 m to the storage body center. The acid fracturing simulation is executed in order to optimize the volumes of fracturing fluids and acid solutions, with an assumed fracture half-length of 110 m, and the results are presented in Fig. 7. The acid fracturing practice involves preflush and alternating injection of vicious cross-linked acid and gelled acid, which leads to etched artificial fractures with desirable lengths.
The operating curve of acid fracturing of Well B is shown in Fig. 8. In the first stage, 50 m$^3$ of base fluids is injected, during which the packer fails. Thus, the bottomhole pressure can be calculated according to the casing pressure, and the length of the artificial fracture can be calculated using the simulator. In the second stage, 170 m$^3$ of cross-linked pad fluid is injected at the rate of 5.1 m$^3$/min under high operation pressures. The casing pressure variation shows that the casing pressure consistently increases and the artificial fracture fully propagates. Alternative injection of cross-linked and gelled acid is treated in the third stage. As the acid injection begins, the tubing pressure declines and the casing pressure steadily grows, because the specific gravity of acid solutions is higher than that of pad fluids. With the injected acid amounts to about 40 m$^3$, the tubing and casing pressures both greatly decline, which implies that the artificial fracture has successfully connects the fracture-and-vug reservoir far away from the wellbore. The leakoff of fluids into the formation rises. Although the pump rate is raised up, the lost volume of injected liquid cannot be sufficiently compensated. At the end of cross-linked acid injection in the second stage, the casing pressure drops to zero, during which the artificial fracture is closed. 30 m$^3$ of the flush fluid is injected in the fourth stage at a lower rate. The reduced flow rate of acid along the artificial fracture facilitates the reaction between the acid and the reservoir penetrated by artificial fractures, and subsequently etched grooves are formed and the conductivity of the etched fracture is improved. The conductivity of etched fractured vs. length of etched fractures based on simulation of the actual pump injection program is presented in Fig. 9. The etched artificial fracture has achieved the desired length, with conductivity of 10 mD·m ~ 47.8 mD·m. Pre-production of Well B is also implemented after acid fracturing, using a 6-mm surface choke. The tubing pressure is 32.06 MPa, with daily oil production of 216.42 m$^3$/d and daily gas production of 58335 m$^3$/d.
3.3. Application of the diverting acid fracturing
The stimulated well section of Well C is from 6018 m to 6075 m. Geophysical prospecting also predicts that the target interval should be a naturally fractured vuggy reservoir. Moreover, Well C has penetrated the favourable storage body presenting strong bead-string seismic reflection display, as is shown in Fig. 10. However, the gas show and well logging demonstrate that the reservoir property near the wellbore is relatively poor. In order to create fractures penetrating through the near-wellbore zone and connecting with the fracture-vug reservoir far away from the wellbore, the acid fracturing technology consisting of injection of “Pad + diverting agents + pad +cross-linked acid” is adopted. Artificial etched fractures extend towards multiple directions, which promotes the odds of artificial fractures connecting with reservoirs containing natural fractures and vugs.

![Figure 10. Planar reservoir distribution mapping based on geophysical prospecting](image)

The operating curve of the temporary-diverting acid fracturing in Well C is shown in Fig. 11. With similar pump rates, the operation pressure increases by about 20 MPa after the temporary plugging agent is injected. After plugging, the operation pressure drops by about 70 MPa. The comparison of operation pressures before and after plugging indicates the acid fracturing has successfully connected the wellbore with the naturally fractured vuggy reservoir. During the post-treatment pre-production with a 4-mm surface choke, the tubing pressure is 14 MPa, the daily oil production amounts to 113 m$^3$/d and the daily gas production reaches 2900 m$^3$/d.

![Figure 11. Treating curve of the temporary-diverting acid fracturing in Well C](image)

4. Conclusions
Based on the analysis upon the geological feature, seismic response, oil and gas show during drilling and well logging, the carbonate reservoir in the Tarim oilfield is classified into four types, namely the ones with large fractures and vugs, with dissolved pores and vugs, with natural fractures and with matrix
pores. The acid fracturing technique presented in this paper is mainly applicable to the naturally fractured vuggy carbonate reservoir.

The acid fracturing design of naturally fractured vuggy carbonate reservoirs is different from the conventional acid fracturing design. The former should be optimized, on the basis the relative position of the geophysical-prospecting-identified fracture-vug storage body against the wellbore as well as the distance between the two. In the case that a certain distance exists between the wellbore and the fracture-vug body, three-dimensional geophysical prospecting interpretation should be implemented to calculate the vertical distance between the center of the favorable storage body and the wellbore. The liquid volume, pump rate and techniques of acid fracturing are then optimized with respect to the calculated distance.

In the case that the wellbore precisely reaches the top of the fracture-vug reservoir, good gas show or well overflow is generally anticipated. Under such conditions, the small-scale acid fracturing is carried out, and high production can be achieved if the etched fracture connects with the top of the fracture-vug storage body.

To create connection with the fracture-vug storage body relatively far away from the wellbore, acid fracturing involving pad or multi-stage injection is implemented. Acid is injected into the formation after the connectivity with the fracture-vug body is built. The pump rate is raised up during the early acid injection to increase the acid-etched length. The pump rate is then lowered during the late acid injection, to improve the conductivity of etched fractures.

In terms of multiple fracture-vug bodies near the wellbore, temporary-diverting acid fracturing should be adopted to simultaneously connect the wellbore with to multiple naturally fractured vuggy reservoirs. The design of such acid fracturing operations should be based on the distance between the wellbore and fracture-vug storage body and the spatial relation between the direction of the maximum principal stress and the fracture-vug storage body.

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