A rock self-supporting high conductivity acid fracturing technique in a deep carbonate reservoir

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Abstract. As carbonate reservoirs in deeper strata continue to develop, reservoir closure stress has significantly increased, where conventional acid fracturing technology cannot maintain acid-etched fracture conductivity and single well production rates are decreasing more quickly. This study proposes a rock self-supporting, highly conductive acid fracturing technique, where the shielding materials cover a portion of the primary hydraulic fracture surface to block the acid rock reaction. After acid injection, the unetched part will be a bearing surface, which serves as a large area and self-supporting high strength rock. This technique fundamentally changes the existing point support pattern of acid-etched fractures. Experimental results demonstrate that when the closed stress is $<$50 MPa, the self-supporting conductivity is 42% higher than the conventionally acid etched fractures. At 90 MPa closed stress, it can still maintain high support strength, which is more than eight times that of a conventional acid etched fracture. The equilibrium relationship between the fracture conductivity and rock support strength was determined using finite element stress simulation and fluid mechanics simulation. The results demonstrate that using a small cylindrical area, dislocation support, and multi-point support is conducive to the dispersion of high closure stress; moreover, the concentrated stress intensity of supporting rock can be reduced by 3–12 MPa. With decrease in supporting area, the stress intensity of the supporting rock is higher. Considering the compressive strength of the rock, the supporting area is $>$25%. When the rock is in the form of a dislocation support, the fluid disperses in the larger void channels, thus effectively maintaining fracture conductivity. The self-supporting acid fracturing technique is useful for increasing the utility of acid fracturing stimulation in deep and ultra-deep wells.

1. Introduction

China’s carbonate rock reserves contain rich oil and gas resources, accounting for ~40% of the world’s total oil and gas reserves. In recent years, with increased exploration and development, more super bathyal facies carbonate reservoirs, such as the Tarim Basin and Sichuan Basin, have been discovered [1-4]. An important characteristic of deep carbonate reservoirs is that the buried depth is $>$6000 m. The Shunbei oil and gas reservoir in Tarim Basin has reached $>$8000 m, and the minimum horizontal principal stress is $>$100 MPa. Without proppant in the acid-etched fracture, fracture conductivity plays a decisive role in the ultimate stimulation effects [5-12]. When the closure stress of the super-deep carbonate reservoir reaches 60–100 MPa, the conductivity of the acid-corroded fracture rapidly decreases, sometimes to zero, leading to corresponding shortening of the effective length of the acid-corroded fracture [13-17]. Thus, the effective period of acid fracturing in super-deep carbonate rock
is relatively short, which seriously restricts the economic benefits of single wells. It is timely and necessary to improve the acid-etched fracture conductivity of deep carbonate reservoirs.

2. Rock self-supporting acid etched fracture conductivity test

Existing acid fracturing technology involves dissolving calcareous minerals in fracture surfaces, leaving the unreacted rock skeleton as the support point. Because of the uneven distribution of each point and its low compressive resistance, it will gradually crush and break under high closure stress. Therefore, to form acid-etched fractures with high conductivity, we are required to completely change the standards of the original fracture point support into the rock surface support.

Rock self-support technology is performed by injecting special shielding materials, covering the surface part of the fracture and injecting acid. The shielding material rock cover has been unetched. If the unetched rock has enough area, covering a portion of the rock bump as the propping fracture, it can overcome the effects of high closure stress. If the rock masses are almost uniformly distributed among one another, the continuously acid-etched fracture channels formed by the surrounding rocks under conditions of high closed stress can maintain stable fracture conductivity for a long time.

Table 1. Experimental scheme of self-supporting conductivity.

| Number | Lithography | Temperature | Acid liquor | Acid injection | Support mode                  |
|--------|-------------|-------------|-------------|----------------|--------------------------------|
| 1      | limestone   | 140°C       | 20% crosslinked acid | 1000 mL        | only acid etched               |
| 2      | limestone   | 140°C       | 20% crosslinked acid | 1000 mL        | shielding materials cover and acid etched |

The carbonate rock slab of the Tahe Oilfield was used as the experimental sample, and the experimental scheme is shown in Table 1. The acid-etched fracture conductivities of injected, 20% crosslinked acid slabs self-supported under different closing stresses were tested; Figures 1–5 show the experimental results.

![Figure 1. Slab with a shielding material.](image)

![Conventional acid etched fracture](image) ![Self-supporting fracture](image)

Figure 2. Lithographically etched fracture morphology.

As shown in Fig. 2, uneven fracture surfaces were formed after the reaction of the crosslinked acid with the rock slabs; moreover, certain grooves were formed at the inlet ends of the fractures. However,
the number of micro-convex bodies supported was limited and unevenly distributed. The shielding material under self-supporting mode effectively covers a portion of the slate surface. After the acid was injected, this part of the area was raised, thus forming the rock cylinder for self-support.

Figure 3. Lithographically etched fracture morphology of conventional acid corrosion.

Figure 4. Lithographically etched fracture morphology of the self-supporting model.

The acid-etched fracture surface was digitized using a 3D morphology scanner to reach the 3D morphology of the fracture surface and the distribution range of the support height. Figures 3 and 4 show that both ends of the conventional acid-etched fracture surface have locally continuous micro-convex supporting points; however, the middle has fewer supporting points and easier to close under high stress, reducing the connectivity of the acid-etched fracture channel and flow capacity of the fluid. The red part of the self-supporting acid-etched fracture is the rock that has not reacted with the acidic liquid, which has a large area and is not easily broken under high closing stress. The statistical distribution range shows that the support heights of the conventional acid-etched fracture surfaces are primarily 605 μm, and certain support heights are only 200–300 μm. The self-supporting acid fracturing technology has a support height of 3000 μm and a minimum support height of 600 μm, indicating that its conductivity has a better protective effect under high closing stress.

Conductivity variations with closed stress under conventional acid-etched fracture, sand-adding mode, and self-supporting conductivity mode were tested (Fig. 5). Self-supporting conductivity formed after the acid rock reaction is higher than conventional acid-etched fracture conductivity and sand adding fracture conductivity. Under a closed stress of 50 MPa, the self-supported conductivity was 42% higher than that of conventional acid etched fracture conductivity, and the closed stress was >60 MPa. The self-supported effect is better than that of ceramic coating, and the supporting strength can be maintained even under a closed stress condition of 90 MPa; moreover, the raised part is not flattened. The conductivity of the acid-etched fracture is more than eight times that of the conventional acid-etched fracture. With larger rock bodies as the support point, planar supports reduce
the stress concentration of a single support point and avoid fracture closure because of the crushing of micro-convex support bodies. Furthermore, compared with proppants, the bulk rock itself has a higher strength, better consolidation ability, and no proppant embedding or blocking of fracture pores; thus, it can maintain the stability of flow channels under high stress conditions better.

![Figure 5. Comparison of fracture conductivity between different support modes.](image)

3. Design of rock support pattern distribution

For realizing self-supporting acid fracturing patterns, the design of the rock self-supporting distribution pattern is the key technology. If the self-supporting area is small, the rock may collapse, although the acid-etched fracture has high conductivity. If the self-supporting area is large, the acid-etched fracture conductivity may be insufficient. Therefore, it is necessary to determine the critical area ratio of self-supporting rock and the distribution of the rock support surface. In this study, finite element stress and fluid mechanics simulations were adopted to calculate the influence of parameters such as different self-supporting models and self-supporting area on the crushing resistance and conductivity of fracture surfaces based on experimental results, so as to determine the feasibility of different self-supporting models and key design parameters.

3.1 Study on self-supporting strength of rock

Considering the elastic–plastic deformation of rock, the finite element simulation method was used to calculate the shapes of different self-supporting rocks, such as the pressure effects of multi-point, cylindrical, and strip, as well as the distribution mode of self-supporting rocks such as the influence of uniform distribution and dislocation cross distribution on the anti-pressure ability.
Figure 6. Stress distribution under different rock self-supporting modes.

As seen from Figure 6, the middle part of the two slats is the pillar left after the dissolution. When the self-supporting rock areas are the same (Figs. 6(a) and 6(b)), the stress concentration of the strip rock is stronger, and the four corners are more likely to break. The cylindrical support indicates that the cylindrical stress is more uniform, and the stress concentration does not easily occur at the boundary. The greater the number of supporting columns, the force on a single supporting body can be reduced by 3–12 MPa (Figs. 6(a), 6(c), and 6(d)). Then, a small cylindrical area and a dislocation, multi-point support is conducive to high closed stress dispersion. Considering the compressive strength of rock, the ratio of the supporting area to the fracture area should be >25%; otherwise, the support column will be broken.

3.2 Analysis of acid-etched fracture flow morphology
The width of the acid corrosion fracture is large, and the flow law of liquid in the fracture does not conform to the applicable scope of Darcy’s law; therefore, Navier–Stokes equations will be used for the calculations.

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} (u_i u_j) = - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right)$$ (1)

The left boundary of the model is defined as the velocity inlet boundary condition, the flow direction is selected as the X direction; however, the right boundary is defined as the pressure outlet boundary condition, the pressure is zero, and other boundary surfaces are defined as wall boundary conditions.
Figs. 7 and 8 show that when rocks are supported in parallel, the boundary layer effect is obvious, and the generated viscous resistance via fluid flow is high. Since supporting rocks obstruct fluid flow, the flow rates between the supports are exceptionally low and the fluids flow primarily from the fracture edges, resulting in a relatively low flow rate. When the rock is misaligned, the fluid disperses in a larger void passage, thus creating a larger area with a higher flow rate. Because of the existence of the rock support, the flow around the support will occur, i.e., a portion of the flow pressure will be lost, which will affect the subsequent streamline distribution.
Flow velocity distribution characteristics under the unsupported area ratio were calculated. With increased area ratios, the flow velocity and flow rate in the outlet section gradually decreased. When the support area ratio was 0.18–0.32, the flow velocity was more appropriately maintained. The fluid could accelerate and decelerate several times before and after the flow supporting rock, resulting in additional pressure loss and affecting the overall flow capacity of the fracture. When there is a large area of support points within the trench, it will produce a streamline and increase local pressure loss. However, when the fluid is in a state of high speed flow, eddy currents will be generated behind the support point, and the eddy swept area will increase with increasing flow rate, invading the effective flow channel and reducing the flow capacity of the acid-etched fracture.

4. Conclusions
(1) The proposed self-supporting high conductivity acid fracturing technology fundamentally changes the existing acid etched fracture support model. Using special materials and technological methods, a part of the rock on the fracture wall is covered and not corroded by acid solution, forming a strong support surface and increasing the stability of the fracture under high pressure.
(2) The experimental results show that under 50 MPa closed stress, the self-supporting conductivity is 42% higher than that of conventional acid-etched fractures. Under conditions of 90 MPa closed stress, it can still maintain high support strength, which is more than eight times that of the conventional acid-etched fracture.
(3) The results show that the method of small cylindrical area, dislocation support, and multi-point support is conducive to dispersing high closure stress, and the concentrated stress intensity of supporting rock can be reduced by 3–12 MPa. With decreasing supporting area, the stress intensity of the supporting rock is higher. Considering the compressive strength of the rock, the supporting area is >25%.
(4) When the rock is in the form of a dislocation support, the fluid flows disperse in the larger void channel, which can more effectively maintain conductivity. When the support area ratio is <0.3, the retention effect of the velocity is enhanced.

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