Multistage Acid-fracturing Increases the Dolomite Production in High Temperature Deep Horizontal Well

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Abstract. The Sinian dolomite reservoirs in Southwest Oil and Gas Field, China, are characterized by HTHP, high stress, low porosity and permeability, large thickness, and presence of natural fractures and holes. Highly deviated well multistage acid fracturing can help expand the contacting area between wellbore and reservoir, thereby increasing the well production. Through experiments, acid fracturing simulations, staging optimization and field applications, some conclusions were obtained. Large-scale physical modelling experiments and numerical simulations show that, given the high horizontal stress difference, presence of natural fractures, can induce a complex fractures networks. The acid systems with different viscosities, such as self-generating acid, gelled acid and diverting acid, are optimized to, in conjunction with high-rate injection and temporary diverting, improve the stimulated reservoir volume and conductivity of acid-fractures in the dolomite reservoirs. The combination of mechanical packers and sliding sleeves facilitate the effective isolation of HTHP dolomite reservoir. The positions of the sliding sleeves are designed according to the high-quality reservoir intervals determined by logging interpretation. The lateral of deviated well is 480m-970m long and stimulated by acid fracturing in 3-6 stages. The post-fracturing tracer testing proves the effectiveness of isolation. This technology was applied for 6 wells, with a daily gas production of (21–110) ×10⁴m³/d after acid fracturing. It provides a new method to increase the production of highly deviated wells or horizontal wells in deep carbonate reservoirs.

1. Introduction
The Gaoshiti and Moxi areas are the main producing areas of Sinian dolomite gas reservoirs in Southwest Oil and Gas Field, China, where the reservoirs are characterized with depth of 5500m-6200m, the temperature of 145°C-180°C, the core matrix porosity of 2.0%-5.0%, and the matrix permeability of 0.001mD-1.0mD. The imaging logging (Figure1) shows that the reservoir contains natural fractures and holes but has strong heterogeneity. As one of the important stimulation techniques, acid fracturing can communicate more dissolved pores and natural fractures. In the Gaoshiti and Moxi areas, the lateral of deviated well in the dolomite reservoir is usually more than 400m long and completed in openhole. The obvious differences of permeability and flow ability between reservoirs make the commingled acid fracturing fail to stimulate the reservoir intervals vertically. To improve the sweep coverage of highly deviated well, the combination of mechanical packers and sliding sleeves were used to isolate the
reservoirs with significant differences in properties, so that these reservoirs can be effectively stimulated. In addition, depending on the length of well section between the reservoirs and the difference in reservoir properties, the deep acid fracturing or diverting acid fracturing was optimized to achieve deep penetrating and uniform stimulation of the reservoirs, which can help to greatly increase the stimulated reservoir volume in vertical and lateral directions. The multistage acid-fracturing can realize the reasonable placement of acid to maximize the production of highly deviated well.

Figure 1. Typical imaging logs of Sinian dolomite reservoir, with natural fractures and holes

2. Research on deviated well multistage acid fracturing

2.1. Physical modeling experiments and numerical simulations
The previous physical modelling experiments on sandstone indicate the impossibility of complex fractures when the horizontal stress difference is greater than 5 MPa. The dolomite reservoirs in the Gaoshiti and Moxi areas contain natural fractures, with the horizontal stress difference up to 10MPa-20 MPa according to logging interpretation. In this study, large-scale physical modelling experiments and numerical simulations were conducted to diagnose if complex fractures can form in dolomite reservoirs with natural fractures under the condition of high stress difference. The samples used were taken from the Sinian carbonate rock outcrops with natural fractures, with the size of 914 mm × 762 mm × 762 mm, and the horizontal stress difference of 15 MPa.

The experiments reveal the new findings in two aspects. First, complex fractures can be formed in carbonate rocks with natural fractures under the condition of high horizontal stress difference. Figure 2 shows the cross-sections of three samples after the experiments. The complexity of fractures networks is decided by the development degree of natural fractures. During the experiments, primary induced fractures occurred along the direction of the maximum principal stress (in S-N direction), and complex branch fractures were also observed. Essentially, the natural fractures of the Sinian reservoirs are mainly open fractures. After the fracturing fluid communicates natural fractures along the primary fractures, the open natural fractures can lead the flow of the fluid, thus inducing a complex network of fractures. Second, changing the values of the injection rate and the fluid viscosity (Q•μ) can affect the forming of complex fractures, which provides an experimental basis for the optimization of fracturing technique to create complex fractures.

Figure 2. Cross-sections of samples after physical modelling experiments
In Figure 2, the obtained $Q\mu$ values (from left to right) are $1 \times 10^{-9}$N•m, $1 \times 10^{-7}$N•m, and $1 \times 10^{-8}$N•m. The low $Q\mu$ value is conducive to the formation of complex fractures near the wellbore. With the fracture propagation and leak-off extension, the $Q\mu$ value gradually decreases, which is beneficial to the formation of far-wellbore fractures. The acid preferentially reacts near the wellbore during the acid fracturing to form highly-conductive acid fractures or fractures networks, so it is advisable to design a high-rate acid fracturing process within the allowable range of operation pressure.

The finite element simulation software was used to simulate under the physical model scale. The simulation unit is shown in Figure 3.a. The fluid viscosity used was 5mPa•s, the horizontal stress difference was 15MPa and the $Q\mu$ was increased by changing the flow rate. The simulation results are shown in Figure 3.b. With the increase of injection rate, a long fracture zone with a certain width is formed, which is favourable for communicating the fracture development zone far away from the wellbore.

![Figure 3.a Simulation unit](image_url)

![Figure 3.b. Numerical simulation results of fractures networks (left injecting rate 60 mL/min, right injecting rate 150 mL/min)](image_url)
2.2. Optimization of isolation for deviated well

At present, there are mainly three open-hole selective completion technologies: (1) selective completion by using hanger + multi-level mechanical open-hole packer + multi-stage fracturing sliding sleeve; (2) selective completion by using expansion liner hanger + multi-level oil-swellable packer + multi-stage fracturing sliding sleeve; and (3) selective completion by using traversable casing packer + multi-stage oil-swellable packer + multi-stage casing. Based on the comparison of the mentioned selective completion technologies and the highly deviated well stimulation process for deep dolomite reservoirs, the multi-level mechanical open-hole packer + multi-stage fracturing sliding sleeve combination was selected as the completion technique for the Gaoshiti and Moxi areas.

The Sinian reservoirs in the Gaoshiti and Moxi areas are highly heterogeneous. The isolation process by numerical simulation for homogeneous reservoir is not suitable for such dolomite reservoirs with natural fractures and dissolved pores. Therefore, an optimal isolation process of open hole was proposed for heterogeneous dolomite reservoir based on mud loss, drilling break, gas cutting/logging responses, and physical properties from logging. To be specific, with consideration to the testing production, the single factors of drilling and well logging responses are analysed, and the main factors controlling the reservoir stimulation are selected; the reservoirs with similar drilling characteristics and physical properties are included in the same stage. Table 1 shows the optimal isolation design for Well XX. In the first and second stages, mud loss and drilling break occurred during drilling. In the third and fifth stages, consistent physical properties were observed by logging interpretation, and there were no mud loss and gas logging abnormality during drilling. In the fourth and sixth stages, the anomaly of gas logging was obvious and the physical properties were similar. In the seventh stage, frequent and successive gas cutting occurred.

| No. | Interval m | Mud loss or Gas show | Effective thickness m | Logging: H·Φ |
|-----|------------|----------------------|----------------------|--------------|
|     |            |                      |                      | Min. | Max. | Avg. |
| 1   | 6110–6243  | Mud loss: 302.1 m³  | 49.4                 | 0.99 | 1.47 | 1.23 |
| 2   | 5940–6110  | Drill break: 1.7 m  | 11.7                 | 0.03 | 0.13 | 0.07 |
| 3   | 5740–5940  | /                    | 8.2                  | 0.04 | 0.15 | 0.09 |
| 4   | 5590–5740  | TG: 4.93%            | 51.2                 | 0.56 | 0.77 | 0.66 |
| 5   | 5460–5590  | /                    | 3.4                  | 0.06 | 0.06 | 0.06 |
| 6   | 5340–5460  | TG: 4.95%            | 8.6                  | 0.05 | 0.13 | 0.08 |
| 7   | 5202–5340  | /                    | 85.5                 | 0.63 | 3.29 | 1.96 |

3. Acid-fracturing process

Physical and numerical simulation results show that changing the fluid viscosity and high-rate injection are beneficial to the formation of complex fractures during acid fracturing. Application of high-pressure operation equipment and reduction of fracturing fluid friction are effective ways to increase the flow rate. According to the previous experience of reservoir stimulation in the Gaoshiti and Moxi areas, the 140 MPa fracturing wellhead and operation equipment can ensure that the flow rate is greater than 7 m³/min. Autogenous acid preflush with low friction and low viscosity (3-30mPa•s) and gelled acid with low-friction and high viscosity (30-45mPa•s) are selected as the acid system. The steering acid with high friction is used for uniform acid placement in long intervals with reservoirs.

The length of the openhole section of highly deviated well in the Sinian dolomite reservoir in the Gaoshiti and Moxi is usually more than 400 m. So, uniform acid placement and temporary plugging & steering techniques are required to improve the drainage of long well section. According to the characteristics of reservoir and the acid fluid distribution in long well section, as well as the technology requirements for fracture reorientation, dissolved temporary plugging agent was applied. As shown in Figure 4, the temporary plugging agent consists of oil powder, granules, and spherical blocking agents of different particle sizes. Laboratory experiments show that the temporary plugging agent blocked the fracture mouth, and the static temporary plugging pressure was greater than 10 MPa.
Figure 4. Temporary diverting agent with different particle sizes

Based on the optimal isolation of heterogeneous dolomite reservoir, the characteristics and differences of reservoirs in each section were identified for purpose of optimization of acid fracturing design. Taking Well XX as an example, the optimal acid fracturing design is shown as follow. According to the reservoir characteristics of each interval in Table 1, specific acid fracturing design principles and process were developed, and the fracturing parameters were optimized using the acid fracturing module of FracproPT software.

Stage one: acid-fracturing with 200m³ gelled acid and pumping rate 6-7m³/min, to bypass the damage.
Stage two: acid-fracturing with 250m³diverting acid, solid diverting agent and injecting rate 4.0-4.5m³/min, assisting to acid fluid diversion.
Stage three: pad acid-fracturing with 200m³ auto-generating acid preflush, 200m³ gelled acid and pumping rate 4.5-6.0m³/min, to make long artificially created acid-fractures to increase drainage area.
Stage four: Acid fracturing with 200m³ auto-generating acid preflush, 250m³diverting acid and pumping rate 4.5-7.0m³/min, to expand the drainage area.
Stage five: acid-fracturing with 200m³ auto-generating acid pad, 200m³ gelled acid and pumping rate 5.0-6.0m³/min, to create long fractures to communicate with natural fractures and holes.
Stage six: acid-fracturing with 250m³ auto-generating acid pad, 250m³ gelled acid and pumping rate 5.0-5.5m³/min, to increase the drainage area.
Stage seven: acid-fracturing with 300m³ diverting acid, 300m³ gelled acid, solid diverting agent and pumping rate 4.5-7.0m³/min, to force acid fluid diversion and create multi artificially acid fractures.

4. Field applications
The deviated well multistage acid-fracturing technology for deep high-temperature dolomite reservoirs was tested in 6 well-times in the Gaoshiti and Moxi areas. In the highly deviated well section with a length of 480-970m, fracturing was conducted in 3-6 stages. The daily gas production after the stimulation is (21-110) ×10⁴ m³/d.

Figure 5 shows the gas production performance of Well XX1 at different time after four stages acid fracturing. The contribution rate of gas production in the four intervals tend to be stable about 6 hours after the start of the test. The contribution rate of gas production in each interval was 22%, 20%, 38%, and 20%, respectively. This proves that the multistage acid fracturing achieves the purpose of improving the drainage area and uniform stimulation.
5. Conclusions
The Sinian dolomite reservoirs in Southwest Oil & Gas Field contain dissolved pores and natural fractures and have strong heterogeneity. The highly deviated well staged acid fracturing technology can help to improve the single well production of such heterogeneous dolomite reservoirs.

The combination of multi-level mechanical open-hole packer + multi-stage fracturing sliding sleeve can achieve effective isolation in deep highly deviated well, thereby improving the longitudinal drainage area of the reservoir.

Based on the characteristics of Sinian dolomite reservoirs, an optimal isolation process of open hole was proposed for heterogeneous dolomite reservoir based on mud loss, drilling break, gas cutting/logging responses, and physical properties from logging.

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