Technology and Application of Segmented Temporary Plugging Acid Fracturing in Highly Deviated Wells in Ultradeep Carbonate Reservoirs in Southwest China

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ABSTRACT: The Shuangyu gas reservoirs in China has a reservoir depth of more than 7000 m and a reservoir temperature of 160 °C. It is a fractured porous carbonate gas reservoir, and the gas wells mainly establish production by acid fracturing. In the early stage, the Shuangyu gas reservoirs was mainly developed with vertical wells. After acid fracturing, the natural gas production was low and declined rapidly. To obtain higher natural gas production, a large number of highly deviated wells have been deployed in the Shuangyu gas reservoirs. Because the diameter of a highly deviated well in the Shuangyu gas reservoirs is small, a subsection tool cannot be operated inside it, so it can only adopt temporary plugging acid fracturing. In this paper, a resistance-reducing acid with low friction resistance is optimized and a set of temporary plugging agents with low dissolution rate in the acid solution are selected through laboratory tests. A dynamic temporary plugging instrument is used to evaluate the plugging ability of a temporary plugging agent with different concentrations and combinations for fractures with widths of 2 and 4 mm, developing a temporary plugging agent formulation suitable for temporary plugging segmented acid fracturing of the Shuangyu gas reservoirs. In the YY666 well, the application of the research results of this paper has successfully achieved a three-stage temporary plugging acid fracturing, and the natural gas production after fracturing has been increased by 3−4 times compared with those of surrounding wells.

1. INTRODUCTION

The Shuangyu gas reservoirs is a fractured porous carbonate gas reservoir with a buried depth of more than 7000 m, a reservoir temperature of 160 °C, an average porosity of 3.62%, and a relatively large permeability distribution range (0.33−31.89 mD). A lot of wells in the Shuangyu gas reservoirs need acid fracturing to establish production capacity.1 The effect of acid fracturing production capacity of vertical wells in the early stage was not ideal, which cannot achieve the goal of quickly building a large gas field. Recently, a number of highly deviated wells have been deployed in the Shuangyu gas reservoirs, and we plan to use segmented acid fracturing to improve the gas well production capacity.

Segmented acid fracturing has the advantages of greatly increasing the seepage radius and increasing the probability of the connecting fracture and cavity.2−5 At present, the segmented acid fracturing of highly deviated wells at home and abroad mainly adopts tool segmented methods, such as drillable bridge plugs, packer and slip sleeves, coiled tubing with packers, layer-by-layer injection of immovable strings, and other technologies.6−8 The above technologies have been greatly used in segmented acid fracturing of oil and gas reservoirs with buried depths of less than 5000 m, but the reservoir depth of high-angle wells in the Shuangyu gas reservoirs is more than 7000 m, the formation temperature is 160 °C, and the outer diameter of the casing is only 114.3 mm. Through investigations, it is known that there is no segmented tool that can withstand a temperature of 160 °C and a pressure of 70 MPa at home and abroad, and the segmented tool cannot be taken out from the well after the segmented acid fracturing construction of an ultradeep well is completed, which will greatly affect the workover operations in the later production process.

In 2008, Schlumberger company first proposed a temporary fiber plugging technology, using degradable fibers to temporarily seal a fracture and forcing the acid fracturing fracture extension direction to change.9 In 2010, Cohen and...
Tardy carried out an experiment of fiber temporary plugging and discussed various factors affecting the effect of fiber temporary plugging. The research on temporary plugging acid fracturing in China started relatively late. In 2014, Zhou and Yi carried out a liquid filtration experiment of temporary plugging artificial fractures with fibers, and analyzed the characteristics of liquid filtration in the process of temporary plugging. In 2015, Jiang Weidong carried out experiments of fiber flow and degradation and found that the fiber had good dispersion in the acid solution, and the performance of the acid solution was not good. In 2016, Zhang selected 120 °C-resistant fibers through tests, and evaluated the sealing ability of fibers and a granular temporary plugging agent for a fracture of width 2 mm. In 2019, Luo established the prediction model of diverting radius and designed the model of fiber dosage.

At home and abroad, there has been no research on temporary plugging acid fracturing of ultradepth and ultra-high-temperature gas reservoirs with buried depth of more than 7000 m and temperature of more than 160 °C, there is no successful example of segmented acid fracturing technology for the Shuangyu gas reservoirs.

Based on the evaluation and optimization of resistance-reducing acid, the dissolution of temporary plugging agent in different temperatures and media is evaluated through laboratory tests. The sealing ability of a temporary plugging agent for fractures with widths of 2 and 4 mm with different concentrations and combinations is analyzed using a test instrument system, and the formulation of the temporary plugging agent suitable for segmented temporary plugging acid fracturing in the Shuangyu gas reservoirs is optimized. The application research results of the YY666 well in the Shuangyu gas reservoirs show that three sections of temporary plugging acid fracturing have been successfully carried out and that average daily output of natural gas after acid fracturing is over one million cubic meters, thus achieving a good increase in production capacity.

2. RESULTS AND DISCUSSION

Shuangyu gas reservoirs is located in the Sichuan Basin, which belongs to the Longmenshan fault fold belt. The reservoir rock is mainly crystalline dolomite, and the reservoir caves and microfractures are relatively developed. According to core statistics, microscopic observation, and imaging logging research, fractures are mainly low-angle fractures with small openings and no large-scale fracture development signs.

The fracture density is not uniform vertically and horizontally, and most of the early structural joints have been completely filled with calcite and asphalt. In the later stage, the fracture is often in the unfilled or half-filled state, and dissolution occurs occasionally along the fracture, and the pore is formed by expanding dissolution.

According to the statistical results of physical properties of 372 samples, the lowest porosity of dolomite in the reservoir is 0.42% and the highest value is 16.51% with an average of 3.11%. The porosity frequency distribution is mainly between 2 and 6%; 77.63% of the samples with porosity greater than 2% account for the total, and the average porosity is 3.6%.

According to the measured data, the temperature in the middle part of formation is 153.75–159.69 °C and the pressure coefficient is about 1.3, belonging to normal-temperature and high-pressure gas reservoirs.

In the early period, acid fracturing was mainly used in vertical wells. The average fluid volume of a single well was 250 m³, and the flow rate of injected acid was 5 m³/min. The output after fracturing was low and decreased rapidly, so it was difficult to form stable production capacity (Table 1).

The following difficulties exist in the segmented acid fracturing of the Shuangyu gas reservoirs: (1) The temperature of the reservoir is as high as 160 °C, and the acid reaction speed increases rapidly with the temperature rise, which greatly affects the acid fracturing length. (2) There is a lack of temperature-resistant packers that can withstand 160 °C and pressure-resistant packers that can withstand 70 MPa, which can meet the requirements of 114.3 mm casing sealing at home and abroad, and the packer operation cycle is long and the cost is high. (3) Temporary plugging agents at home and abroad generally have problems such as low temperature resistance (<140 °C), low pressure tolerance (<15 MPa), poor sealing ability for wide fractures, etc.

2.1. Study on the Resistance-Reducing Acid. The high friction of the acid used in the Shuangyu gas reservoirs in the early period has affected the acid fracturing length. Increasing the acid-flow rate can greatly increase the length of acid corrosion fracture. In this paper, a resistance-reducing acid is studied, which can not only maintain a high viscosity at 160 °C and pressure-resistant packers that can withstand 70 MPa, which can meet the requirements of 114.3 mm casing sealing at home and abroad, and the packer operation cycle is long and the cost is high. (3) Temporary plugging agents at home and abroad generally have problems such as low temperature resistance (<140 °C), low pressure tolerance (<15 MPa), poor sealing ability for wide fractures, etc.

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The frictional resistance of the resistance-reducing acid and water.
reducing acid is about 30% of that of water, which can effectively improve the injection displacement in the construction process.

To meet the technical requirements of large-capacity acid fracturing in ultradepth and high-temperature wells, acid gelling agent must have dual characteristics of high temperature resistance and low friction. We add gelling agent to 20% HCl solution, and the gelling agent is a copolymer of sodium acrylate and acrylamide. We heated the acid from room temperature to 160 °C and then naturally cooled it to normal temperature. The difference in viscosity of the acid before and after the constant temperature is a measure of the thermal stability of the gelling agent at 160 °C. The viscosity of the resistance-reducing acid solution is 33 mPa·s at room temperature, and there is still 20 mPa·s at 160 °C after being stabilized for 4 h, indicating that the resistance-reducing acid has good thermal stability at 160 °C.

Test conditions: The carbonate rock in the Sichuan Basin of China is used for the experiment, and the fracture width of the rock plate is 2 mm. We have tested the conductivity of the acid fracture stimulated with the resistance-reducing acid under the conditions of injection speed of 20 ml/min and temperature of 140 °C.

Through Figure 2, we can know that with the increase in closing pressure, the conductivity of the acid corrosion fracture decreases gradually. Under the condition of closing pressure of 50 MPa, the acid-corrosion fracture studied in this paper, still has relatively good conductivity, indicating that the resistance-reducing acid can achieve effective acid corrosion of the fracture.

**2.2. Performance Evaluation of the Temporary Plugging Agent.** A high-performance temporary plugging agent is the key to the implementation of segmented acid fracturing technology. In this paper, we have evaluated many kinds of temporary plugging agents and selected a granular polyacrylamide temporary plugging agent to be used in the segmented acid fracturing of the Shuangyu gas reservoirs.

By testing the dissolution of the temporary plugging agent under different temperature and solvent conditions, we can judge the dissolution type, dissolution time, and dissolution rate of the temporary plugging agent and provide a basis for the design of segmented temporary plugging acid fracturing.

The following conditions shall be met for the temporary plugging agent: (1) The dissolution rate of the temporary plugging agent in acid solutions is very small avoiding its rapid dissolution in acids. (2) The dissolution rate of the temporary plugging agent during construction is less than 30% (calculated according to 500 m³ of construction fluid between two levels and the estimated construction time is about 2 h); (3) The temporary plugging agent can be completely degraded in 6–8 h under the formation temperature to avoid damaging the reservoir.

**Table 2. Solubility Test Results of the Temporary Plugging Agent in Different Solvents (at 20 °C)**

| serial number | solvent        | initial weight (g) | weight at 16 h of reaction (g) | dissolution rate (%) |
|---------------|----------------|--------------------|--------------------------------|----------------------|
| 1             | water          | 3                  | 3                              | 0                    |
| 2             | 20% HCl        | 3                  | 3                              | 0                    |
| 3             | oil            | 3                  | 3                              | 0                    |
| 4             | resistance-reducing acid | 3       | 3                              | 0                    |

The test results are shown in Tables 2 and 3. It can be seen that at room temperature, the temporary plugging agent is insoluble in water, oil, acids, and other different solvents. The dissolution rate of the temporary plugging agent in water, 20% HCl and the resistance-reducing acid was less than 30% after reaction at 160 °C for 4 h. The results show that the selected temporary plugging agent has good resistance to high temperature and acids. It reacts at 160 °C for 8 h, and the temporary plugging agent is completely dissolved in water and oil to ensure that the reservoir will not be damaged after the construction.

**2.3. Pressure-Resistance Test of the Temporary Plugging Agent.** Temporary plugging evaluation flow device can be used to simulate the ability of the temporary plugging agent to bear pressure under different fracture width conditions.

(1) Prepare a certain amount of the temporary plugging agent carrying liquid and put it into the intermediate container.

(2) According to the required crack width, adjust the thickness of the gasket between the special metal rock plates, and put the special metal rock plates into the cavity of the diversion chamber.

(3) Place the guide chamber on the press, connect the pipeline, and the liquid outlet leads to the measuring cylinder.

(4) Apply a certain confining pressure to the diversion chamber with a press.

(5) Start the liquid injection pump to inject liquid at a certain displacement. Stop the pump when the pump pressure reaches the value to be measured or when the pump pressure reaches a certain value and breaks through.

(6) The distribution of the composite temporary plugging agent with different sizes in the joint can be further analyzed by taking out the special metal rock plate.

(7) After setting the width of the joint, the concentration of the temporary plugging agent under the condition of the width of the joint is optimized by comparing the maximum bearable pump pressure under different temporary plugging agent concentrations or the amount of liquid used under the same maximum pump pressure.
According to the FMI logging and core observation results, the natural fracture opening range of the Shuangyu gas reservoirs is 24 mm, and the fracture widths set in this test are 2 and 4 mm.

In the process of acid fracturing, the fracture width changes with the injection rate. The fracture software is used to simulate the fracture width at different rates, and the results are shown in Figure 3. It can be seen from Figure 3 that with the decrease of injection rate, the fracture width decreases gradually. When the injection rate is 2 m$^3$/min, the fracture width is 2.5 mm. The small fracture width is conducive to the formation of a sealing layer in the fracture by the temporary plugging agent.

The temporary plugging agent used in this paper is granular polyacrylamide temporary plugging agent, whose diameter is 1 mm.

2.3.1. Test on the Ability of the Temporary Plugging Agent to Block 2 mm Fracture Width. In this paper, the sealing ability of the temporary plugging agent for a fracture with a width of 2 mm is studied when the concentration of the temporary plugging agent is 1.5, 2, and 2.5%, respectively.

The temporary plugging agent with a concentration of 1.5% is used to block the 2 mm fracture, and the pressure reaches 14 MPa at 25 min (Figure 4), which can be maintained. There are four sudden pressure changes in the process of the test. It is speculated that the plugging layer formed in the early stage of the test is relatively weak. After the pressure increases, the structure of some plugging layers is destroyed. With the injection of more temporary plugging agent, the broken part of the plugging layer is blocked, so the pressure rises rapidly.

A temporary plugging agent with a concentration of 2% is used to block 2 mm fracture (Figure 5). When the test time reaches 21 min, the pressure rises rapidly, indicating that the temporary plugging agent has formed an effective plugging layer in the fracture.

It can be seen from the test that when the concentration of temporary plugging agent is 1.5, 2, and 2.5%, the fracture with a width of 2 mm can be effectively sealed (Figure 7). However, the effective sealing time of different concentrations of temporary plugging agent is different, and the fastest sealing time is when the concentration of the temporary plugging agent is 2.5%.

2.3.2. Test on the Ability of the Temporary Plugging Agent to Block 4 mm Fracture Width. The test shows that when the concentration of the temporary plugging agent is 1.5%, the fracture with a width of 4 mm cannot be effectively sealed.

### Table 3. Solubility Test Results of the Temporary Plugging Agent in Different Solvents (at 160 °C)

| serial number | solvent                | initial weight (g) | weight at 4 h of reaction (g) | dissolution rate (%) | initial weight (g) | weight at 8 h of reaction (g) | dissolution rate (%) |
|---------------|------------------------|--------------------|-------------------------------|----------------------|--------------------|-------------------------------|----------------------|
| 1             | water                  | 3                  | 2.30                          | 23.3                 | 3                  | 0                            | 100                  |
| 2             | 20% HCl                | 3                  | 2.13                          | 28.8                 | 3                  | 0                            | 100                  |
| 3             | resistance-reducing acid | 3               | 2.15                          | 28.1                 | 3                  | 0                            | 100                  |
| 4             | oil                    | 3                  | 2.26                          | 24.5                 | 3                  | 0                            | 100                  |

Figure 3. Change of fracture width under different injection rates.

![Figure 3](image-url)

Figure 4. Sealing test of 2 mm fracture when the concentration of temporary plugging agent is 1.5%.

![Figure 4](image-url)

Figure 5. Sealing test of the 2 mm fracture when the concentration of the temporary plugging agent is 2%.

![Figure 5](image-url)
sealed and there is no pressure rise in the test process (Figure 8). The analysis shows that it may be because the concentration of the temporary plugging agent is too low to effectively seal the fracture.

Through the test, we can find that when the concentration of the temporary plugging agent is increased from 1.5 to 2.5%, it can effectively block the fracture with a width of 4 mm. After 39 min, the pressure rises to 13.9 MPa and remains stable for a long time (Figure 9). Although the temporary plugging agent with a concentration of 2.5% can block the wide fracture, the effective plugging time is too long to quickly form the temporary plugging layer.

To improve the plugging efficiency, we try to add 0.5% granular temporary plugging agent into the 2.5% concentration of the temporary plugging agent. Through the test, we can find that after adding 0.5% granular temporary plugging agent, the plugging time is shortened from 39 to 27 min, which meets the site construction requirements (Figure 10).

Combined with the above test results, considering that the fracture width distribution range of the Shuangyu gas reservoirs may be large, to improve the plugging efficiency, we suggest that 2.5% temporary plugging agent + 0.5% granular temporary plugging agent should be used for segmented temporary plugging acid fracturing of the Shuangyu gas reservoirs to achieve the purpose of effective sections.

2.3.3. Optimization of Injection Rate During Temporary Plugging. Three-dimensional fracturing software is used to simulate the fracture width under different rates. When the injection rate is 6 m³/min, the fracture width is 11 mm. When the injection rate is reduced to 3.5 m³/min, the fracture width is 6 mm. When the injection rate is reduced to 2.5 m³/min, the fracture width is 4 mm. According to the test results of different combinations of temporary plugging agents, when the fracture width is less than 4 mm, it is favorable for temporary plugging. Therefore, we suggest to reduce the injection rate to 2.5 m³/min after the completion of a section of acid fracturing to form a high-strength temporary plugging layer quickly and achieve the purpose of segmented acid fracturing.

2.3.4. Field Application. Well YY666 is a highly deviated well in the Shuangyu gas reservoirs. The maximum deviation is 88.8°, the drilling depth is 7859 m, the reservoir temperature is 161 °C, the average porosity is 5%, and the average permeability is 2 mD. In recent years, we have injected a temporary plugging agent into the YY666 well two times in three stages of acid fracturing. We injected 1160 m³ of a resistance-reducing acid with a construction displacement of 6–8 m³/min. After the completion of the first and second stages of construction, we injected temporary plugging agent to
block fractures formed by acid fracturing. After the temporary plugging agent was injected on-site, the construction pressure rose rapidly, indicating that the temporary plugging is effective. After segmented temporary plugging acid fracturing, the test production of this well is several times higher than those of the surrounding wells, and it can produce 1 million cubic meters of natural gas per day. Well YY610 did not use the segmented acid fracturing technology, and its daily gas output after fracturing was only $2.4 \times 10^5$ m$^3$ (Figure 11). 11

3. CONCLUSIONS

(1) The resistance-reducing acid selected by this evaluation has the advantages of high temperature resistance and low friction resistance. The injection flow rate of the construction site is increased from 5 to 8 m$^3$/min using this acid. The construction with a large flow rate is conducive to reducing the reaction rate of acid and increasing the length of acid corrosion fractures.

(2) A single temporary plugging agent cannot effectively block the fracture with width larger than 2 mm. A granular temporary plugging agent with a concentration of 0.5% and a temporary plugging agent with a concentration of 2.5% can effectively block the fracture with a width of 4 mm. This formulation has been successfully applied in the YY666 well.

(3) The successful results of the YY666 well show that segmented temporary plugging acid fracturing can greatly improve the production effect of super-deep reservoirs, such as the Shuangyu gas reservoirs.

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Notes
The authors declare no competing financial interest.

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■ REFERENCES

(1) Zeng, J.; Ma, H.; Liu, J.; Gou, B.; Li, J.; Yang, L. An acid fracturing technology suitable for high-temperature ultradeep gas wells in the Qixia Formation in the north of Western Sichuan. Oil Drill. Prod. Technol. 2019, 364–367.

(2) Geng, Y.; Zhang, Y.; Han, Z.; Zhao, W. Acid fracturing technique for fractured-vuggy carbonate reservoir by horizontal well process in Tahe oil field. Xinjiang Pet. Geol. 2011, 89–91.

(3) Yang, Q.; Huang, Y.; Liu, P.; Zhao, L.; Din, D. Research and application of composite acid fracturing technology with fiber diversion temporary plugging in ultra-deep carbonate horizontal wells. Pet. Geol. Recovery Effic. 2015, 117–121.

(4) Wang, D.; Zhou, F.; Ge, H.; Shi, Y.; Yi, X.; Xiong, C.; Liu, X.; Wu, Y.; Li, Y. An experimental study on the mechanism of degradable fiber-assisted diverting fracturing and its influencing factors. J. Nat. Gas Sci. Eng. 2015, 27, 260–273.

Figure 11. Acid-fracturing treatment curve.
(5) Chen, J.; Weng, D. CNPC’s progress in horizontal well fracturing technologies for unconventional reservoirs. *Nat. Gas Ind.* 2017, 37, 79–84.

(6) Zhang, B.; Xue, C.; Zhou, L.; Zhang, Y. Application of multistage acid fracturing technology for horizontal well to ultra-deep fractured carbonate reservoirs. *Xinjiang Pet. Geol.* 2013, 232–234.

(7) Han, T.; Li, H.; Fan, Y. Segmention fractuing of naked hole horizontal well leading internation. *Pet. Equip.* 2012, 62–63.

(8) Zhang, R.; Hou, B.; Zhou, B.; Yongjian, L. Effect of acid fracturing on carbonate formation in southwest China based on experimental investigations. *J. Nat. Gas Sci. Eng.* 2020, 73, No. 103057.

(9) Solares, J. R.; Al-Harbi, M.; Al-Sagr, A. M. In Successful Application of Innovative Fiber-Diverting Technology Achieved Effective Diversion in Acid Stimulation Treatments in Saudi Arabian deep Gas Producers, Paper SPE-115528-MS Presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Perth, Australia, Oct 20–22, 2008.

(10) Cohen, C. E.; Tardy, P. M. J.; Lesko, T. M. In *Understanding Diversion with a Novel Fiber-Laden Acid System for Matrix Acidizing of Carbonate Formations*, Paper SPE-134495-MS Presented at the SPE Annual Technical Conference and Exhibition, Florence, Italy, Sept 19–22, 2010.

(11) Zhou, F.; Yi, X.; Yang, X.; Liu, X.; Wang, D. Dynamic Filtration Experiment of Fiber Temporary Plugging Artificial Fracture. *Drill. Prod. Technol.* 2014, 83–85.

(12) Jiang, W.; Liu, H.; Yan, J.; Liang, C.; He, A. A novel fiber temporary plugging and diverting acid fracturing technology. *Nat. Gas Ind.* 2015, 54–56.

(13) Zhang, X.; Geng, Y.; Jiao, K.; Hou, F.; Luo, P. The Technology of Multistage Acid Fracturing in Horizontal Well for Carbonate Reservoir by Temporary Plugging Ways in the Tahe Oilfield. *Pet. Drill. Tech.* 2016, 82–85.

(14) Luo, Z.; Wu, L.; Zhao, L. Design method and application of temporary plugging by fiber and diverting acid fracturing. *Reservoir Eval. Dev.* 2019, 65–69.