Parameter Optimization of Pre-stage CO_2 Fracturing

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Abstract: As a core technology for the efficient and green stimulation of unconventional oil and gas reservoirs, pre-stage carbon dioxide (CO_2) fracturing relies on the unique properties of CO_2 including low viscosity, high diffusivity, easy phase transition, and energy enhancement for flowback improvement. It can effectively reduce reservoir breakdown pressure, activate natural fractures, mitigate water-sensitive formation damage, and facilitate carbon sequestration. However, current field applications are constrained by several critical issues, such as poor matching of injection parameters, insufficient accuracy in fracture network regulation, difficult wellbore phase-state control, and an imbalance between cost and benefit, which severely restrict its stimulation potential. Based on the fundamental mechanisms of pre-stage CO_2 fracturing, this paper systematically analyzes the key influencing factors for process optimization. Combined with the petrophysical properties of shale oil reservoirs in Sichuan, the CO_2 injection volume and rate are optimized, providing theoretical support for the efficient development of this block.

Keywords: Pre-stage CO_2 fracturing, Process optimization, Unconventional oil and gas.

1. Introduction

With the continuous advancement of oil and gas exploration and the growing global demand for oil and gas resources, unconventional oil and gas resources such as tight oil, shale oil and shale gas have become an increasingly important component of energy supply [1]. Unconventional reservoirs generally require stimulation to improve their permeability, and hydraulic fracturing serves as an effective technique for enhancing oil and gas recovery. Conventional hydraulic fracturing suffers from problems including high water consumption, secondary formation damage, and low flowback efficiency of fracturing fluid, which significantly impair the stimulation performance. Due to its favorable physical properties and positive effects on reservoir stimulation, CO_2 is often used in auxiliary fracturing to improve the effectiveness of reservoir stimulation [2–4].

Pre-stage CO_2 fracturing technology refers to the reservoir pretreatment by injecting liquid or supercritical CO_2 prior to the main fracturing operation. This technology can effectively reduce the reservoir breakdown pressure by 10% to 30%, enhance the complexity of fracture networks and the stimulated reservoir volume (SRV), and simultaneously cut down water consumption and waste liquid treatment pressure, which aligns with the concept of low-carbon development. It has been industrially applied in multiple blocks including Sichuan, Daqing and Jimusar oilfields.

Nevertheless, the pre-stage CO_2 fracturing process is affected by multiple factors, such as reservoir conditions, injection parameters, fluid compatibility and equipment performance. The existing process design mostly relies on empirical formulas, resulting in prominent problems including inaccurate parameter optimization, unreasonable phase state control, and failure of fracture network morphology to match reservoir requirements. Consequently, issues like severe CO_2 filtration, insufficient proppant-carrying capacity and below-expectation post-fracturing production enhancement have emerged in some well intervals. Therefore, carrying out research on the optimization of pre-stage CO_2 fracturing process, clarifying the optimization objectives and establishing scientific optimization methods are of great theoretical and engineering significance to break through technical bottlenecks, improve the effect of reservoir stimulation and reduce construction costs.

2. Mechanism of CO_2 Enhanced Oil Recovery

The essence of pre-stage CO_2 fracturing process optimization is to maximize the effects of CO_2 in mechanical resistance reduction, energy enhancement for flowback improvement, and reservoir modification by regulating injection parameters, fluid systems, operation modes and other key factors, so as to achieve the optimization goals of lowering breakdown pressure, creating complex fractures, reducing formation damage and improving development efficiency. Its core mechanism is based on the multi-field coupling interaction between CO_2, reservoir rocks and in-situ fluids, which can be divided into the following three aspects:

2.1. Viscosity Reduction and Dissolution Effects of CO_2

Compared with conventional hydraulic fracturing, pre-stage CO_2 energy-storage fracturing exhibits advantages such as reducing crude oil viscosity, dissolving formation minerals, improving the displacement efficiency of formation crude oil, and increasing the complexity of fractures. Therefore, it shows good adaptability for reservoir stimulation in low-permeability and ultra-low-permeability tight oil reservoirs [5-7]. When CO_2 dissolves into the formation fluid, it can create a weakly acidic environment, which exhibits favorable solubility for dolomite and calcite in the formation minerals. This effectively improves the micro-pore and throat structure in the formation [8].

2.2. Role of CO_2 Extraction in Enhancing Shale Oil Recovery Efficiency

Previous studies have shown that the supercritical state exhibits diffusivity similar to gases and dissolving power similar to liquids, characterized by low viscosity and low interfacial tension. This enables it to rapidly penetrate into the micro-pores of shale oil reservoirs. Furthermore, CO_2

possesses the capability to extract crude oil components. As the injection volume and pressure increase, its capacity to extract heavy-end components gradually enhances. The synergistic effect between pre-stage CO_2 and the main fracturing fluid (such as slickwater, crosslinked fluid, etc.) serves as the key to process optimization.

When CO_2 dissolves into crude oil, it causes the oil to swell, reduce in viscosity, and become lighter, thereby improving fluid mobility. Its dissolution in water forms weak carbonic acid, which mildly dissolves reservoir minerals and enhances permeability. Meanwhile, the energy-enhancing effect of CO_2 drives the rapid flowback of fracturing fluid and flowback liquid, reducing reservoir damage caused by water lock and Jamin effect. This makes the technology particularly suitable for water-sensitive clay reservoirs [9-10].

2.3. Supercritical CO_2 Facilitates Increased Stimulation Degree of Artificial Fractures

Supercritical CO_2, the most common phase state under formation conditions, features viscosity similar to that of gases and a diffusion coefficient dozens of times higher than that of liquids. This enables it to rapidly invade micro-fractures and matrix pores of the reservoir. By transmitting pore pressure, it reduces the effective stress on the rock, thereby lowering the breakdown pressure and providing favorable conditions for fracture initiation and propagation. Due to its low viscosity and strong penetration capability, supercritical CO_2 easily opens bedding fractures or natural fractures. This facilitates the formation of a more complex fracture network compared to conventional water-based fracturing fluids, increasing the contact surface area between artificial fractures and the reservoir, and improving the reservoir volume controlled by a single well.CO_2 creates a uniform pore pressure field within the reservoir. It preferentially activates natural fractures and induces shear failure, avoiding the propagation of a single dominant fracture and enhancing the complexity of the fracture network [11-12].

3. Optimization of Key Factors for Pre-pad CO_2 Fracturing Technology

The key parameters of pre-stage CO_2 fracturing mainly include CO_2 injection volume, injection rate, injection pressure, fluid slug combination, injection time and phase state control parameters. The optimization follows the basic principles of adapting to reservoir conditions, giving priority to fracture network construction, reducing construction risks and improving economic benefits, so as to realize the precise coupling of parameters and reservoir adaptability. Among them, CO_2 injection volume and injection rate are the most critical control parameters, which directly affect the pressure accumulation effect near the wellbore, the activation degree of natural fractures and the scale of stimulated reservoir volume.

Reasonable CO_2 injection volume is the premise to ensure the pre-fracturing energy storage effect. Too small injection volume cannot form an effective pressure field and fail to reduce the breakdown pressure and activate natural fractures; while excessive injection volume will increase construction costs, aggravate CO_2 filtration loss, and even lead to the risk of early fracture breakthrough and proppant accumulation. Combined with the porosity, permeability and natural fracture development degree of the target reservoir, the injection volume is optimized to ensure that CO_2 can fully penetrate the matrix and fracture system, and lay a good foundation for the expansion of main fracturing fractures.

Injection rate control directly affects the fracture propagation morphology. A moderate and stable injection rate is conducive to the uniform diffusion of CO_2 in the reservoir, forming a balanced pore pressure field, and promoting the synchronous initiation and expansion of multi-directional micro-fractures; an excessively high injection rate is likely to cause rapid pressure rise, induce single main fracture expansion, reduce fracture network complexity, and increase the pressure of wellbore and ground equipment; an excessively low injection rate will lead to slow pressure accumulation, long construction period, and reduced construction efficiency. For tight shale oil reservoirs, the injection rate is optimized by combining numerical simulation and indoor physical simulation experiments to realize efficient and complex fracture network construction.

A numerical reservoir model was developed incorporating the petrophysical parameters of shale oil reservoirs in Sichuan: reservoir burial depth of 3000 m, average pay zone thickness of 20 m, porosity of 6.4%, permeability of 0.01 mD, initial formation pressure of 30 MPa, and reservoir temperature of 75 ℃. Numerical simulations were implemented using a three-dimensional, three-phase compositional model in reservoir numerical simulation software.

Table 1. Basic parameters of the numerical model

Depth/m	Layer Thickness /m	Pressure /MPa	Porosity/%	Permeability /mD	Fracture Spacing/m	Fracture Half-length /m	Horizontal Section Length/m	Fracture Permeability /mD
3000	20	30	6.4	0.01	100	80	2000	4500

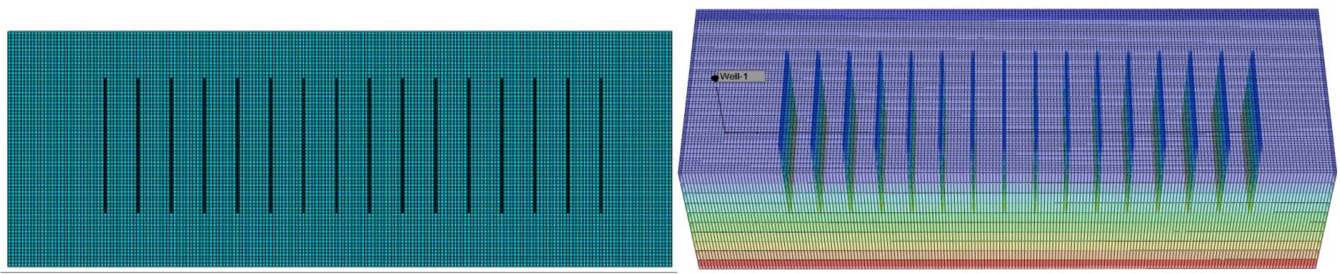
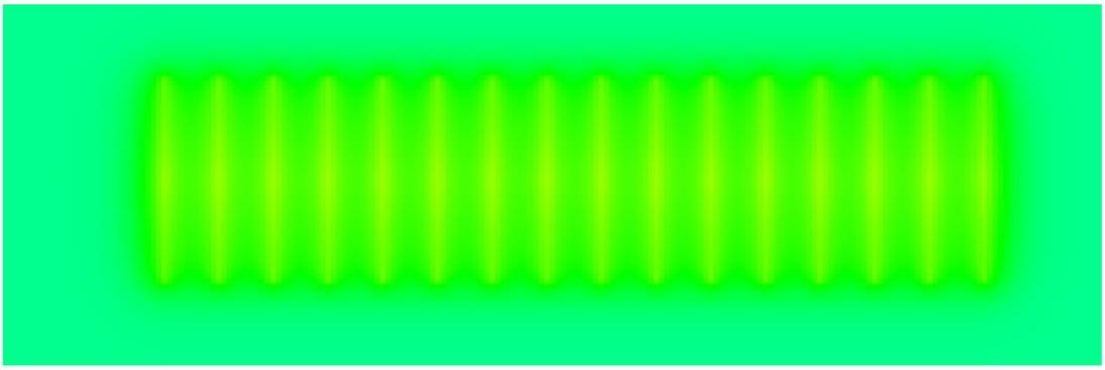


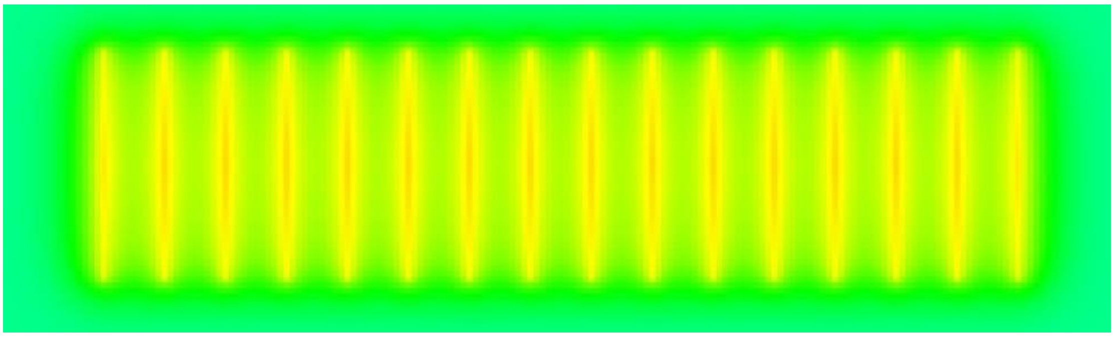
Figure 1. 3D numerical model of shale oil fracturing reservoir

3.1. Optimization of CO_2 Injection Volume

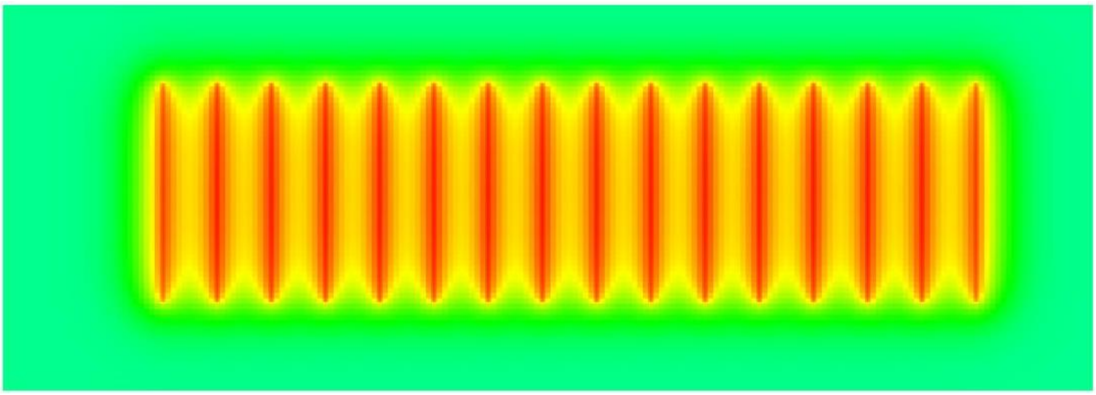
The injection volume of CO_2 per stage was set to 300–400 m^3 with a displacement rate of 4 m^3/min. Formation pressures under different CO_2 injection volumes were simulated, and the results are shown in Fig. 2. The energy swept range was positively correlated with the injection volume. With the increase in CO_2 injection volume, both the energy swept area and formation pressure gradually increased. When 350 m^3 of CO_2 was injected, the interference between fractures was minimal; however, when the injection volume exceeded 350 m^3, further increasing the CO_2 dosage led to significant mutual interference between fractures. Therefore, the optimal CO_2 injection volume was determined to be 350 m^3.



a. 300m^3



b. 350m^3



c. 400m^3

Figure 2. Formation pressure under different CO_2 injection volume

3.2. Optimization of CO_2 Injection Rate

Figure 3 presents the variation law of formation pressure with injection time of liquid CO_2 at different injection rates (3, 4, 5, 6 m^3/min), reflecting the impact of injection rate on the formation pressure distribution of CO_2. The higher the injection rate, the faster the pressure rises, and the larger the injection volume within the same duration, accompanied by a steeper pressure increase amplitude. This is conducive to the rapid diffusion of CO_2 into reservoir pores and the expansion of the swept volume. Therefore, the optimal injection rate of CO_2 is determined as 5 m^3/min.

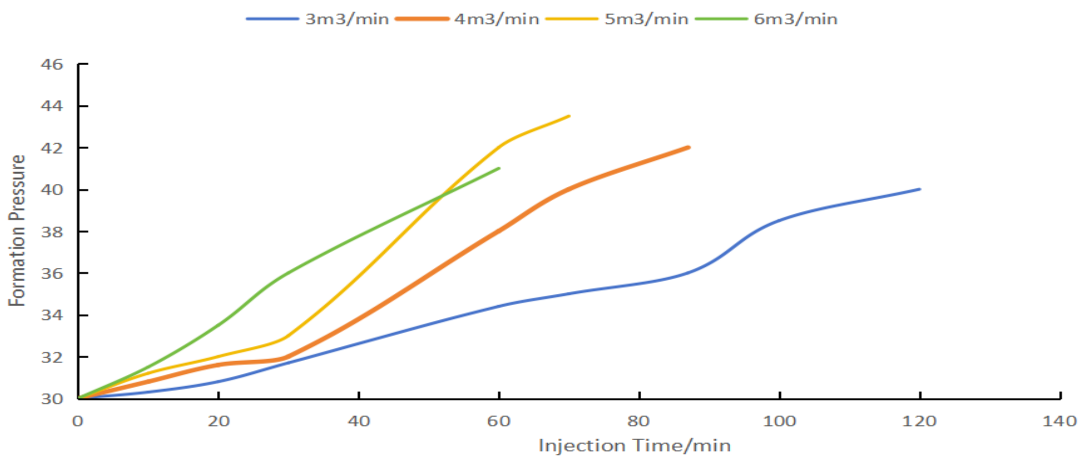


Figure 3. Variation of formation pressure with time under different injection rates

4. Analysis of Application Effect

According to the field test results of pre-stage CO_2 fracturing in Sichuan shale oil reservoirs, Well Text 1 adopted the pre-stage CO_2 fracturing technology with optimized process parameters, featuring a CO_2 injection rate of 5 m³/min and a total injection volume of 4000 m³. Compared with other wells in the same well pad, the cumulative liquid production and oil production of a single well are significantly improved, which verifies that the optimized construction parameters are adaptable to the development of this block.

Table 2. CO_2 pre-fracturing well process parameters and production performance

Well No.	horizontal section length/m	CO_2 injection volume/m³	CO_2 injection rate/m³/min	Total liquid volume/m³	Total sand volume/m³	Pumping rate/m³/min
Text well 1	1800	4000	5	45800	3100	18-20
well 2	1750	\	\	43700	3000	18-20
well 3	1600	\	\	42000	3050	18-20

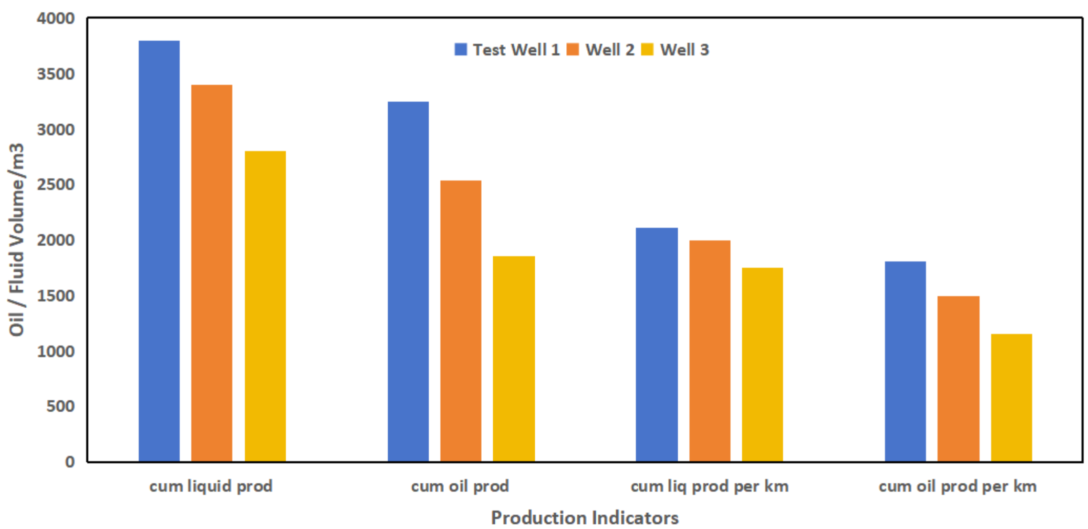


Figure 4. Comparison of Production Performance Between CO_2 Prepad Fracturing Wells and Conventional Fracturing Wells

5. Conclusion

The CO_2 pre-fracturing technique utilizes the miscible displacement effect between CO_2 and in-situ crude oil, which remarkably reduces crude oil viscosity, enhances fluid flow flexibility and seepage capability, and improves oil mobility. Meanwhile, the physical and chemical dissolution of CO_2 on reservoir rocks effectively connects natural fractures and matrix pores, forming a more complex and high-conductivity 3D fracture network. This significantly improves reservoir permeability and stimulation degree, thereby achieving the objectives of high-efficiency stimulation and long-term stable production for oil and gas wells.

Based on numerical simulation for operation parameter optimization, a higher injection volume corresponds to a wider energy-affected region. The recommended injection volume is 350 m³ per stage, which can effectively supplement formation energy while avoiding fracture interference. The optimal injection rate of 5 m³/min is favorable for rapidly elevating formation energy.

Field application results demonstrate that, compared with conventional fracturing wells, wells treated with CO_2 pre-fracturing achieve considerably higher production performance, presenting obvious advantages in quality improvement and production enhancement.

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