Research and Application of Comprehensive Evaluation of Engineering Sweet Spot in Block LX

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Abstract. Block LX is a tight sandstone gas reservoir with low porosity and low permeability, and there are the problems of a sharp decline in production and a poor utilization degree of superimposed reserves in the longitudinal gas bearing sand body within a few years after the initial fracturing, which leads to the difficulty of gas field production replacement under the condition of high comprehensive decline rate. By analysing the effect of reservoir characteristics and rock mechanical properties on volumetric fracturing, combined with geological logging data and rock mechanics experimental data of tight sandstone reservoir in Block LX, the paper tries to study the adaptive effect of volumetric fracturing technology in Block LX. The adaptability of volumetric fracturing is evaluated by software simulation of fracturing effect to determine the optimal fracturing construction parameters before the volumetric fracturing gas test is carried out on three wells. The gas test results show that the daily gas production is increased by more than 46.01% compared with that before volumetric fracturing, and the fracturing effect is good. Therefore, it is feasible to use volumetric fracturing technology to overcome the difficulty of low permeability and low gap in Block LX to improve gas production.

1. Introduction
Volumetric fracturing refers to that, in the process of hydraulic fracturing, the natural fractures are expanded by special technological measures, with shear slip of brittle rocks and formation of interweaving fracture networks of natural fractures and artificial fractures, so as to increase the volume of reservoir reconstruction to improve production and recovery [1].

Volumetric fracturing technology has become a key technology for efficient development of tight reservoirs [2-6] and has been successfully applied and promoted in foreign countries, especially in North America [8]. In 2008, PetroChina began to test and apply the net fracturing technology. In 2009, it began to test and apply the volumetric fracturing technology, and in 2010, it initially established the volumetric fracturing technology system. In 2014, Mu Hailin [9]explored the application of volumetric fracturing technology used in shale gas reservoir reconstruction to tight sandstone reservoir, and then put forward some understandings of volumetric fracturing of tight sandstone. Although Block LX is a tight sandstone reservoir, its characteristics are quite different from those of tight reservoirs in North America, and there are few feasibility studies on volumetric fracturing in this reservoir. Therefore, it is of great significance to analyze the reservoir conditions to realize volumetric fracturing from a theoretical point of view, to conduct comprehensive evaluation of engineering sweet spot, and then to evaluate the effect of
volumetric fracturing in Block LX so as to effectively improve gas production by using volumetric fracturing technology in Block LX subsequently.

2. Comprehensive Evaluation Method of Engineering Sweet Spot

2.1. Evaluation of Development Potential

The evaluation of development potential is mainly based on the productivity coefficient and reservoir coefficient to analyze the reserve abundance and productivity potential of each layer of gas reservoir. Meanwhile, based on the characteristics of reservoir physical properties, a criterion is established to evaluate the relative degree of development potential of each layer.

- Productivity coefficient = permeability multiply by effective thickness
- Energy storage coefficient = gas saturation multiply by effective reservoir thickness × porosity

2.2. Evaluation of Compressibility

Rock brittleness is an inherent property of rock failure under stress, and it is characterized by a small plastic strain occurring before the macroscopic fracture, which is all released in the form of elastic energy.

Vertical fractures are formed under the joint action of the minimum horizontal principal stress and the tensile stress generated by the fracturing fluid, and the stress-strain field is formed at the top and bottom of the fractures. Based on Irwin fracture mechanics theory, when the stress intensity factor reaches its critical value, the fracture will expand forward. Thus, it can be concluded that fracture toughness $K_{IC}$ can be used as a parameter to characterize the fracture ability of hydraulic fracturing and indicate the difficulty of reservoir fracturing. The smaller the value is, the stronger the fracture ability of hydraulic fracturing is, and the more conducive it is to hydraulic fracturing.

Based on the brittleness index and Type I fracture toughness, the following evaluation method is formed as:

$$F_I = B_{ln} K_{IC \cdot D}$$

$$B_{ln} = \frac{B_I - B_{Imin}}{B_{Imax} - B_{Imin}}$$

$$K_{IC \cdot D} = \frac{K_{C_{max}} - K_{IC}}{K_{IC_{max}} - K_{IC_{min}}}$$

2.3. Degree of Natural Fracture Development

Natural fracture development degree = integrity coefficient * fracture development degree * rock stability coefficient

Integrity coefficient ($K_V$)

$$K_V = \left[\frac{v_M}{v_K}\right]^{\frac{2}{3}}$$

In the formula, $v_M$ is the longitudinal wave velocity of rock mass, i.e. the longitudinal wave velocity obtained by logging.

$v_K$ is the longitudinal wave velocity of rock, i.e. the theoretical longitudinal wave velocity of rock skeleton.

The ratio $KV$ reflects the integrity of rock mass, that is, the more complete the rock mass is, the larger the $v_M$ is, and the closer it is to $v_K$, and the greater the $K_V$ will be.
Degree of fracture development \( (R_F) \)

\[
R_v = \frac{(E_{ma} - E)}{E_{ma}}
\]  \hspace{1cm} (5)

In the formula, \( E \) is the dynamic elastic modulus of rock mass, which is obtained directly from logging data. \( E_{ma} \) is the dynamic elastic modulus of rock skeleton, which is obtained from the theoretical value. \( E \) is related to the fracture degree of rock mass. The more fractured the rock mass is, the smaller \( E \) will be, while \( E_{ma} \) is a constant for the same kind of rock, so \( R_F \) will be larger. Therefore, \( R_F \) eliminates the influence of rock properties on \( E \) and highlights the degree of rock fragmentation.

Rock stability coefficient \( (R_g) \)

\[
R_g = K_b G
\]

In the formula, bulk modulus \( K_b = 1/C_b \) and shear modulus \( G = \rho_b \alpha/\Delta t_s \).

The mechanical parameters of rock reflect the mechanical properties of rock, and the rock is not real steel, so the study of its elastic mechanical properties is one of the main methods to analyze fracture development. Theoretically, the variation characteristics of rock mechanical parameters with fractures are as follows: the development of fractures will increase the time difference of shear wave, and the rock density will decrease in varying degrees, thus resulting in the decrease of Young's modulus and shear modulus of rock.

2.4. Coefficient of Horizontal Stress Difference

When the difference between the maximum horizontal principal stress and the minimum principal stress is large, the fracturing effect is usually a single double-winged fracture. If the stress difference is small, the direction of fracture initiation will be affected by the natural fractures in the formation, and fractured fractures will communicate the natural fractures to extend in all directions, thus forming a fracture network system. Therefore, the horizontal stress difference has an important effect on the complexity of fracture network.

\[
K = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{\sigma_{\text{min}}}
\]  \hspace{1cm} (6)

Based on the above indexes, combined with the reservoir physical properties, rock mechanical properties and in-situ stress distribution, the index optimization method is formed.

| Table 1. Parameter judgment method. |
|-------------------------------------|
| Indicator                           | Advantage | Disadvantage |
| Energy storage coefficient          | ≥0.073    | <0.073       |
| Productivity coefficient            | ≥1.2      | <1.2         |
| Compressibility coefficient         | ≥0.2      | <0.2         |
| Coefficient of horizontal stress difference | <0.25    | ≥0.25        |
| Degree of natural fracture development | \( R_F > K_v \) | \( R_F < K_v \) |

2.5. Application of Comprehensive Evaluation Method

When the difference between the maximum horizontal principal stress and the minimum principal stress is large, the fracturing effect is usually a single double-winged fracture. If the stress difference is small, the direction of fracture initiation will be affected by the natural fractures in the formation, and fractured fractures will communicate the natural fractures to extend in all directions, thus forming a fracture network system. Therefore, the horizontal stress difference has an important effect on the complexity of fracture network.
2.5.1. Evaluation of Development Potential

![Evaluation of Development Potential](image1)

It can be seen from the figure that there is no industrial air flow in the four types of reservoirs after fracturing operation, and there are many wells suspected of flooding. The average open flow of Type 2 well after fracturing operation is large, and the energy storage coefficient of Type 2 well is higher than that of Type 3 reservoir, so its reconstruction effect is slightly better than that of Type 3 reservoir. However, the energy storage coefficient and productivity coefficient of Type 1 reservoir are both good, but due to the reservoir characteristics of low porosity and ultra-low permeability, it is possible that reservoir damage may lead to unsatisfactory reconstruction effect.

2.5.2. Evaluation of Compressibility

![Compressibility Evaluation](image2)

Fig 1. Evaluation of development potential.

Fig 2. Compressibility evaluation.
It can be seen from the figure that the average open flow of compressibility of Type 1 reservoir is significantly lower than that of Type 2 reservoir, but the well sections with obvious fracturing effect are more than that of Type 2 reservoir, thus the reservoir with poor compressibility can be obtained. Moreover, the number of producing wells and no-gas wells of Type 2 reservoir is significantly increased, so it is necessary to optimize fracturing construction parameters and supporting technology.

2.5.3. Evaluation of Complex Fracture Network

![Fig 3. Feasibility evaluation of complex fracture network.](image)

It can be seen from the figure that the overall development degree of natural fractures in Linxing-Shenfu Block is relatively low, and the horizontal principal stress difference is large, which is not conducive to the formation of complex fracture network. Therefore, it is necessary to conduct a targeted analysis for different layers and well sections to find the geological conditions conducive to the formation of complex fracture network.

3. Application

3.1. Optimal Design of Fracturing Process

Based on the comprehensive analysis of natural fracture development, horizontal principal stress difference and brittleness index of Block LX, the paper believes that Block LX has the implementation conditions of volumetric fracturing to increase production, that is, volumetric fracturing to expand natural fractures and form fracture network to solve the production problem of low porosity and low permeability for the reservoir. Using the geological characteristic data mentioned above, the author decides to adopt the casing packer staged fracturing scheme, guided by low displacement and low sand ratio as well as fracturing fluid system with gel breaking capacity at low temperature, and focus on the analysis and optimization of fracture morphology simulation software for construction parameters such as sand amount and main displacement, which can effectively expand the scale of fracture network and improve the adaptability of volumetric fracturing and the block.

| Sand amount m³ | 20  | 30  | 40  |
|----------------|-----|-----|-----|
| fracture length| 152.4 | 181.8 | 208.3 |
| Support length | 147.9 | 178.3 | 203.4 |
| Dynamic fracture height | 33.7 | 39.1 | 43.3 |
| Support fracture height | 32.7 | 38.3 | 42.4 |
Table 3. Of fracture dimensions corresponding to construction displacement (sand quantity 20 m$^3$).

| Construction displacement m$^3$/min | 3   | 4   | 5   |
|------------------------------------|-----|-----|-----|
| Fracture length                    | 188.4 | 181.8 | 176.4 |
| Support length                     | 185.8 | 178.3 | 172.2 |
| Dynamic fracture height            | 39.0  | 39.1  | 39.8  |
| Support fracture height            | 38.2  | 38.3  | 39.1  |

Fig 4. Simulation of fracture extension software.

The volumetric fracturing technology is adopted in the field stimulation test of Well A. After the perforation by tubing transmission, 9.2 m$^3$ liquid nitrogen coupled injection fracturing is performed with 20 m$^3$ of 20/40 mesh sand with casing packer at a main flow rate of 3 m$^3$/min.

3.2. Effect Analysis

The volumetric fracturing technology is used for three wells in Block LX for preliminary demonstration to provide data for subsequent application research of volumetric fracturing. The gas test results are shown in Table 4. As seen from the table, the highest value of daily gas output is 20182.5 m$^3$, and the average value is 11920 m$^3$. Compared with the pre-compression productivity, the average increase is 65.53%, of which the highest increase is Well B and the lowest is Well C. The comparison shows that the use of volumetric fracturing technology can effectively increase production. To further illustrate the effectiveness of volumetric fracturing stimulation, taking Well A in Table 5 for example, the fracture monitoring after volumetric fracturing shows that its surface volume with volumetric fracturing is 314,000 m$^3$, and the volume affected by the fracturing is 1,632,000 m$^3$, with the main fracture length of 190 meters and a maximum fracture height of 60 meters. The scale of the fracture network is larger than expected in the construction design. Moreover, the three-dimensional effect of fracturing monitoring results is shown in Figure 5.
Table 4. Fracturing parameters and post-compression effect.

| Well number | Reservoir parameter | Construction parameter | Post-compression productivity | pre-compression productivity | Productivity growth |
|-------------|---------------------|------------------------|-------------------------------|-------------------------------|---------------------|
|             | porosity%           | Permeability md        | Sand amount m³                | Sand Ratio %                  | Main displacement m³/min | Daily gas output m³/d | Daily gas output m³/d | Growth rate% |
| A           | 5.6                 | 0.17                   | 26.1                          | 21.56                         | 3.34                | 11880                 | 7137               | 66.46       |
| B           | 7.9                 | 0.2                    | 40                            | 20.8                          | 3.7                 | 16808-20182.5         | 10780              | 71.57       |
| C           | 14.1                | 2.1                    | 19.65                         | 18.3                          | 2.96                | 5385                  | 3688               | 46.01       |
| average     | \                   | \                      | \                            | \                            | \                   | 11920                 | 7201               | 65.53       |

Table 5. A well fracturing monitoring results.

| Fracture characteristics | main fracture length | fracture half-length | vertical depth of main fracture | Orientation of main fracture | Fracture height | Fracturing surface volume | design value |
|--------------------------|----------------------|----------------------|---------------------------------|-----------------------------|-----------------|--------------------------|--------------|
| fracturing network       | 190m                 | 120m                 | 1575-1595m                      | N30°E                       | 60m             | 314000 m³                | 188.4m       |
| swept parameters         | East-West            | 160m                 | North-South                     | 170m                        | swept volume    | 1632000 m³               | 39m          |

Fig 5. Three-dimensional diagram of fracture monitoring.

4. Conclusion

1. Combined with the engineering geological characteristics and parameters of tight sandstone gas reservoir, the comprehensive evaluation and optimization method for the engineering sweet spot of volumetric fracturing is established. Meanwhile, the fracturing operation data and well test data are used to verify the results, which are consistent with the field fracturing effect.

2. According to the analysis and study of geological conditions suitable for the implementation of volumetric fracturing technology, the natural fractures of the reservoir in Block LX are well developed, and the rock brittleness index is generally high, and the horizontal principal stress difference of the reservoir is in the range of 1 to 8MPa, which reservoir characteristics meet the basic reservoir conditions for the volumetric fracturing process to increase production.
Through the numerical simulation analysis and the comprehensive analysis of the field fracturing gas test results of typical wells, the fracture network after fracturing exceeds the design expectation, and the daily gas output increases significantly. Therefore, the volumetric fracturing technology has good stimulation effect and good adaptability in this block.

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