Case Study: Effect of Natural Fracture on Stimulation Strategy in Keshen Tight Gas

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Abstract. Aimed at problems of poor fracturing effects of fracture-network acid fracturing in three wells in the Keshen 5 block, a fractured and tight gas reservoir in Tarim Oilfield, the mechanical activity of natural fractures was studied. The fractures in this block were divided into three types: fully-filled, semi-filled, and unfilled. The analysis of the correlations showed that the correlation of the number of fully-filled fractures and absolute open flows (AOF) is poor, while the correlation between the number of unfilled and semi-filled fractures and AOF is the best. Core samples with different types of fractures were tested using conventional triaxial compression methods, and the experimental results showed that the friction coefficient of the fully-filled fracture is close to that of semi-filled fracture, while the cohesion of fully-filled natural fractures is close to that of intact rocks, which is much greater than that of semi-filled fractures. The effective stress test results show that the effective stress coefficient of fully-filled natural fracture rock samples is lower than that of semi-filled fractures. Using Mohr–Coulomb theory to calculate the natural fracture mechanics of high-production wells and low-production wells, the results show that low-production wells are mainly fully-filled fractures, most of which are not activated, so the production is low; while high-production wells are semi-filled and unfilled fractures, most of which can be activated, so the production is high. Based on this, for a well dominated by fully-filled fractures, it is recommended to use conventional gel fracturing to replace the fracture-network acid fracturing process. The stimulation practice of two wells has proven the validity of this strategy. The filling degree of natural fractures affects the increasing production and choice of stimulation process. This may be a relatively new understanding and may provide insights to stimulation strategy decisions for other fractured tight reservoirs in the world.

1. Introduction

The Keshen 5 block gas reservoir in the Kelasu gas field is located in the Keshen section of the Keshen area in the Kelasu structural belt of the Kuqa foreland thrust belt in the Tarim Basin. The target layer is the Lower Cretaceous Bashkikik Formation with a thickness of about 300 m. The gas reservoir in the block has a medium depth of 6697.32 m, and the formation pressure in the middle of the gas reservoir is 109 MPa. The porosity of the reservoir is 4%~7%, and the permeability is 0.01×10⁻³μm²~0.1×10⁻³μm². Structured fractures are well developed in this block. The fractures are dominated by high-angle fractures and diagonal fractures, and the overall performance is ultra-low porosity and ultra-low permeability fractured sandstone gas reservoirs [1-4].

Numerous practices in the early stage of the Keshen block have realized that if fractures are developed, non-crosslinking fracturing fluid and mud acid composite fracture-network acid fracturing is used. If the fractures are not developed, gel and hydraulic fracturing are used. Until now, six evaluation
wells have been drilled in the block: KS501, KS502, KS503, KS504, KS505, and KS506, and the well positions are shown in Figure 1. KS504 and 505 are placed in the east of the Keshen 5 block, while KS501, 503, and 506 are located in the west of Keshen 5 block. Fractures in these six wells developed. Therefore, the fracture-network acid fracturing was applied to all six wells. Among them, KS503, KS504, and KS505 have better effects and higher open hole potential, while KS501, KS506, and KS508 are less effective, which is an order of magnitude smaller than those three wells and far from expected (Table 1). It is interesting to note that even with the same fracturing process in the same block, the production difference is so vast.

![Figure 1. Structure map of Keshen 5 block.](image)

**Table 1.** Comparison of acid fracturing and fracturing stimulation effects in Keshen 5 block.

| Well No. | KS501 | KS503 | KS504 | KS505 | KS506 | KS508 |
|----------|-------|-------|-------|-------|-------|-------|
| AOF, 10^4 m^3/d | 24 | 50.37 | 501.91 | 345.42 | 34 | 24 |

This article first analyzes the statistical relationship between the fracture filling degree and production, and then, it conducts triaxial compression tests and permeability tests on three different types of fractures to obtain the mechanical parameters and effective stress coefficients of the fracture. Again, the Mohr–Coulomb criterion is used to analyze the mechanical activity of the fracture. Finally, the relationship between production and fracture filling degree is analyzed, and technological measures are proposed.

2. Correlation analysis of fracture filling degree with production

Keshen 5 is a portion of fractured tight sandstone gas. Fractures are hydrocarbon channels and closely related to production. Therefore, it is necessary to deeply analyze the impact of fractures on production.

Geologists have divided the fractures into three types according to the filling degree of the fractures\[5\], which are fully-filled, semi-filled, and unfilled. The filling is basically calcite or argillaceous, and the fractures are mainly high-angle oblique fractures-vertical fractures, as shown in the figure below.

![Figure 2. Fully-filled fractures. (a) KS501, 1-1/48, (b) KS501, 4-20/57.](image)
Figure 3. Semi-filled fractures. (a) KS501, 4-25/57, (b) KS503 2-2/40.

Figure 4. Unfilled fractures. (a) KS503, 2-2/40, (b) KS505, 3-65/90.

KS501, KS504, and KS505 were cored, and the number of fractures of different fracture types was obtained through quantitative description of the core, as shown in Table 2.

The number of fractures observed in the core, coring length, and target layer thickness can be used to estimate the number of fractures in the entire reservoir thickness.

\[ N = \text{Density} \times \text{Height} \times \text{Ratio} \]  \hspace{1cm} (1)

Among them, \( N \) is the number of fractures, \( \text{Density} \) is the fracture density, \( \text{Height} \) is the reservoir thickness, and \( \text{Ratio} \) is the proportion of the type of filling.

| Item                        | KS501 | KS504 | KS505 |
|-----------------------------|-------|-------|-------|
| Coring length, m            | 20    | 15    | 40    |
| Target layer thickness, m   | 253   | 306   | 250.5 |
| Core fracture number        | 76    | 61    | 64    |
| Core fully-filled fracture number | 63   | 42    | 23    |
| Core semi-filled fracture number | 11.5 | 11    | 6     |
| Core unfilled fracture number | 1.5  | 8     | 35    |

Image logging has been implemented for wells KS503, KS506, and KS508, and the number of fractures in the three types of filling has been identified, as shown in Table 3.

| Item                        | KS503 | KS506 | KS508 |
|-----------------------------|-------|-------|-------|
| Total number of fractures   | 119   | 107   | 120   |
| Number of fully-filled fractures | 86   | 104   | 91    |
| Number of semi-filled fractures | 13   | 0     | 0     |
| Number of unfilled fractures | 20   | 3     | 29    |

Based on the data in Tables 2 and 3, the relationship between the number of fractures in six wells, the number of fully-filled fractures, the number of unfilled fractures, the number of semi-filled and unfilled fractures, and the production can be established in the block, as shown in Figure 5. The correlation coefficient between the total number of fractures and production is 0.3801, which shows that there is good correlation between fractures and production. However, the correlation coefficient between the number of fully-filled fractures and production is 0.1884, and the correlation is poor. The correlation coefficient between the number of unfilled & semi-filled fractures and the production reaches 0.8461, which is optimal. This is because productivity is related to permeability\(^6\). The permeability of fully-filled fractures is very poor, and the number of fractures has poor correlation with AOF. The other two types of fractures have high permeability. The more the number of fractures, the greater the
comprehensive permeability, so there is a strong correlation. The statistical results show that semi-filled and unfilled fractures have greater contributions to production, while fully-filled fractures have a smaller contribution to production.

![Figure 5. Correlation between the number of fractures and production.](image)

It is necessary to analyze the correlation between production and fracture aperture. For the descriptions of KS501, KS504, KS505, and KS506 core fractures, the average value of fracture aperture can be obtained as 0.2, 0.5, 0.1, and 0.1 mm, respectively. Combined with Table 1, the correlation coefficient between fracture aperture and production can be established as 0.448. In fact, the fracture filling and fracture aperture have a correlation trend. The smaller the fracture aperture, the easier the calcite filling, and the aperture of fractures unfilled or semi-filled is generally larger.

This shows that the semi-filled and unfilled fractures have the most direct contribution to production, while the fully-filled fractures may not significantly contribute to production.

That is to say, semi-filled & unfilled fractures constitute a good flow channel, while fully-filled fractures do not effectively communicate with the reservoir. Therefore, it is necessary to analyze the mechanism from the perspective of geomechanics.

![Figure 6. Correlation between fracture aperture and AOF.](image)

3. Fracture geomechanical activity analysis
The difference in production is related to the volume of the fracture network, and the volume of the fracture network is directly related to the number of activated-fractures. According to the theory of
Barton and Zoback\cite{7,8}, critical stress fractures are in a hydraulically conductive state, while fractures that have not reached the critical stress state are in a hydraulically closed state. Therefore, whether the fracture is activated can be judged by analyzing the critical stress state of the fracture. The critical stress state of natural fractures is related to in-situ stress, fracture mechanical parameters, Biot coefficient, and fracturing pressure.

| No. | Group No. | Well No. | Depth (m) | Fracture angle (°) | Confining pressure (MPa) | Temperature (℃) | Compressive strength (MPa) | Fracture filling type |
|-----|-----------|----------|-----------|-------------------|------------------------|-----------------|--------------------------|---------------------|
| 1   | 3 - 1     | KS2-2-8  | 6735.07   | 40                | 40                     | 130             | 95.0                     | Semi-filled fracture |
| 2   | 3 - 2     | KS2-2-8  | 6735.10   | 40                | 40                     | 130             | 199.0                    |                     |
| 3   | 3 - 3     | KS2-2-8  | 6735.13   | 40                | 40                     | 130             | 163.0                    |                     |
| 4   | 3 - 4     | KS2-2-8  | 6735.16   | 40                | 60                     | 130             | 342.0                    |                     |
| 5   | 3 - 5     | KS2-2-1  | 6800.68   | 40                | 80                     | 130             | 398.0                    |                     |
| 6   | 4 - 1     | KS2-2-8  | 6820.18   | 20                | 60                     | 130             | 411.0                    |                     |
| 7   | 4 - 2     | KS2-2-8  | 6820.21   | 30                | 60                     | 130             | 409.0                    |                     |
| 8   | 4 - 3     | KS2-2-8  | 6820.24   | 35                | 60                     | 130             | 477.0                    |                     |
| 9   | 4 - 4     | KS2-2-8  | 6820.27   | 40                | 60                     | 130             | 508.0                    |                     |
| 10  | 5 - 1     | KS2-2-8  | 6812.62   | 40                | 60                     | 100             | 691.1                    | Fully-filled fracture|
| 11  | 5 - 2     | KS2-2-8  | 6812.65   | 40                | 60                     | 100             | 684.3                    |                     |
| 12  | 5 - 3     | KS2-2-8  | 6812.68   | 25                | 60                     | 100             | 606.6                    |                     |
| 13  | 5 - 4     | KS2-2-8  | 6812.71   | 20                | 60                     | 100             | 625.0                    |                     |
| 14  | 5 - 5     | KS2-2-8  | 6812.85   | 30                | 60                     | 150             | 389.4                    |                     |
| 15  | 5 - 6     | KS2-2-8  | 6812.88   | 30                | 60                     | 150             | 382.0                    |                     |
| 16  | 5 - 7     | KS2-2-8  | 6812.91   | 20                | 60                     | 150             | 417.6                    |                     |
| 17  | 5 - 8     | KS2-2-8  | 6812.94   | 25                | 60                     | 150             | 285.2                    |                     |

### 3.1. Mechanical parameters of fracture surface
To understand the effects of the degree of filling on the fracture mechanical parameters, a fracture mechanical parameter test was carried out. The mechanical parameters of the rock matrix and fracture surface can be determined by triaxial compression test. If the angle between the fracture direction and the axial load direction (force-fracture angle) is 25–40\cite{39}, the fracture will take precedence over the rock itself before it breaks. For this reason, 17 fully-filled and semi-filled core plungers (unfilled rock fails to remove the rock sample) (Figure 7), and the parameters of the force-fracture angle and the test results are shown in Table 4.

![Figure 7](image_url)

**Figure 7.** Picture before the core test. (a) fully-filled core plunger, (b) semi-filled core plunger

Unlike intact rocks, strength parameters are no longer determined by the envelope of a series of Mohr circles, but the normal stress and shear stress of the fracture surface at a given angle $\psi$ must be determined. Using the confining pressure and maximum axis pressure to make the Mohr circle of the triaxial test, intersect two points with the abscissa, make a straight line at an angle $\psi$ to the vertical line.
from the left intersection point, and intersect the Mohr circle at the point $A$ to obtain the normal stress and shear stress at the fracture surface. Under different confining pressures, a section of points is obtained, and the strength parameters of the fracture surface can be obtained by linearly fitting these points\cite{7}. The mechanical parameters equation of semi-filled fractures is $\tau = 0.79\sigma$, as shown in Figure 8. The cohesion of semi-filled fractures is very low, which can be basically ignored according to the analysis of experimental data. The mechanical parameters equation of the fully-filled fractures is $\tau = 0.84\sigma + 47.29$, as shown in Figure 9.

![Figure 8. Data fitting of mechanical parameters of semi-filled fractures.](image)

![Figure 9. Data fitting of mechanical parameters of fully-filled fractures.](image)

For comparison, three sets of complete rock mechanical compression tests were also conducted, and the average mechanical parameters equation of Mohr Coulomb strength was obtained as $\tau=0.93\sigma+48$, as shown in Table 5.

**Table 5. Complete rock triaxial test data.**

| Well Name | Depth (m) | Sample    | $C$ (MPa) | $\phi$ (°) | UCS (MPa) |
|-----------|-----------|-----------|-----------|------------|-----------|
| KS2-2-4   | 6699.36   | KS2-2-4-42D | 50 | 43 | 230.0 |
| KS2-2-8   | 6721.73   | KS2-2-8-18B | 49 | 42 | 223.7 |
| KS2-1-5   | 6731.78   | KS2-1-5-55C | 45 | 45 | 221.6 |
|           | 6734.35   | KS2-1-5-64C | 30 | 42 | 135.8 |

Triaxial compression test results show that the mechanical strength parameters of fully-filled and semi-filled (unfilled) fractures in ultra-deep tight sandstone are significantly different. The friction coefficient of fully-filled and semi-filled (unfilled) natural fractures is close, but the cohesion of fully-filled natural fractures is very large, almost close to the cohesion of intact rocks, and much larger than other common rocks\cite{10}.

![Diagram showing mechanical properties of fractures](image)
3.2. Style and spacing
It is necessary to understand the effect of fracture filling degree on effective stress conversion efficiency. It is easy to understand that the Biot coefficient of semi-filled and unfilled fractures can take a value of 1, while the Biot coefficient of fully-filled fractures can be estimated through experimental tests.

In this study, we mainly used the pore volume compression experiment to measure the Biot coefficient. The measurement results are shown in Table 6. The average value of the Biot coefficient is 0.685, which is consistent with the published literature. The Biot coefficient of fully-filled fractures can be approximated as 0.685.

![Figure 10. Data fitting of mechanical parameters of fully-filled fractures.](image)

### Table 6. Biot coefficient test.

| No. | Sample NO. | Core Sample Depth (m) | Biot Coefficient |
|-----|------------|------------------------|------------------|
| 1   | 11-2       | 6796.79                | 0.650            |
| 2   |            |                        | 0.620            |
| 3   | 43-2       | 6800.65                | 0.727            |
| 4   | 56         | 6805.57                | 0.703            |
| 5   | 85-2       | 6807.55                | 0.697            |
| 6   | 101        | 6867.76                | 0.584            |
| 7   | 113        | 6869.23                | 0.699            |
| 8   | 138        | 6873.41                | 0.733            |
| 9   | 140-1      | 6873.66                | 0.742            |
| 10  | 154        | 6876.46                | 0.658            |
| 11  | 169        | 6879.02                | 0.726            |

3.3. Comparative analysis of natural fracture activation
Wells KS501 and KS505 were selected as analysis examples. Among them, KS501 mainly is fully-filled fractures, while KS505 mainly is semi-filled and unfilled fractures. The reservoir depth, pore pressure, in-situ stress, and bottom hole construction pressure of these two wells are shown in Table 7.

### Table 7. In-situ stress of Keshen 5 block.

| Well No. | Reservoir Middle-Depth (m) | Pp SG | Sv SG | SHmax SG | Shmin SG | Azimuth of SHmax | Maximum construction pressure gradient SG | Biot Coefficient | Friction Coefficient | Cohesion |
|----------|----------------------------|-------|-------|----------|----------|-----------------|--------------------------------------------|-----------------|----------------------|---------|
| KS501    | 6300-6600                  | 1.69  | 2.45  | 2.65     | 2.0      | 87              | 2.2                                        | 0.685           | 0.84                 | 47      |
| KS505    | 6620-6920                  | 1.65  | 2.45  | 2.65     | 2.0      | 179             | 2.15                                       | 1               | 0.79                 | 0       |

The results of the activity analysis of natural fractures in KS501 well are shown in Figure 11. It can be seen that under fracturing pressure conditions, natural fractures are not activated. Regression analysis of the fracturing pressure curve of KS501 well is shown in Figure 12. There are no activation characteristics of natural fractures, which is consistent with the analysis results.

Similarly, to calculate the activity of natural fractures in well KS505, when the equivalent density of the bottom mud pressure mud is 2.15, most of the fractures open, as shown in Figure 13. Therefore, under the current fracturing conditions, the natural fractures of this well are mostly in an activated state.
4. Process measures and application

Due to the large cohesion of fully-filled natural fractures and the small Biot coefficient, it cannot be activated under the current construction pressure conditions. In other words, the fracture-network acid fracturing measures are not effective for this type of reservoir. Therefore, although the fractures are developed, if the fully-filled fractures are the main type, the conventional gel fracturing process should be used, and if the semi-filled and unfilled fractures are the main type, the fracture-network acid fracturing or fracture-network fracturing should be used.

According to this idea, the KS501 and KS506 wells in the four low-production wells were subjected to gel fracturing, and the unobstructed flow rate reached 2 million cubic meters. After the reconstruction, the unobstructed flow rate was increased by an order of magnitude, and the effect was obvious.

Using well KS506 as an example, the first acid fracturing section of the well was 6406.0-6578.0 m, and hydraulic fracturing was carried out again. The conventional fracturing was carried out with jelly fracturing fluid, and the perforation span was 172 m. From the construction curve, after the fiber enters the formation with sand fluid, the pressure response is obvious, the pressure rises about 12 MPa, and the construction pressure difference between the two stages is large, while the average construction pressure of the second stage is about 10 MPa higher than the first stage (Figure 14), indicating that the fiber has a significant turning effect with sand. From the production curve (Figure 15), the oil pressure and gas production increase rapidly with decreasing fluid production after hydraulic fracturing. Compared with
the pre-fracture, the maximum production is three times that before the reconstruction, indicating that through the hydraulic fracturing, reservoir fractures are well communicated and the effect is obvious. In this way, knowledge of the optimized stimulation process based on the developmental characteristics of natural fractures in the Keshen 5 block has been upgraded.

![Figure 14. KS506 hydraulic fracturing construction diagram.](image1)

![Figure 15. KS506 production curve after hydraulic fracturing.](image2)

5. Summary
Triaxial compression tests show that the friction coefficients of fully-filled and semi-filled natural fractures in Keshen 5 block are close, but the cohesion of fully-filled natural fractures is close to that of intact rocks, which is much greater than that of common rocks. At the same time, the Biot coefficients of fully-filled natural fracture rock samples are much lower than that of semi-filled and unfilled fractures. The analysis of natural fracture activation conditions shows that under construction pressure, fully-filled fractures cannot be activated, while semi-filled and unfilled fractures can be activated. Therefore, semi-filled and unfilled fractures are effective fractures and have important production contributions.

Based on these results, we have upgraded the knowledge of optimized stimulation process of the Keshen 5 block, which is based on the characteristics of natural fracture development. Although the fractures are developed, if the fully-filled fractures are the main type, conventional gel fracturing process is still used, and if the semi-filled and unfilled fractures are the main type, fracture-network acid fracturing or fracture-network fracturing continues to be used.

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