Practical Analysis of Deep Coalbed Methane Stimulation

Taiyuan Formation Coal Seam of Daniudi Gas Field

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Abstract. The research on the effective utilization of deep coalbed methane (with a burial depth of over 2500 m) within the Sinopec system is still blank, while the Daniudi gas field has conducted practical exploration for the fracturing development of coal seams in the Taiyuan Formation of the Carboniferous Permian. The coal seam of the Taiyuan Formation in the Daniudi Gas Field is buried at a depth of 2500–3000 m, and overall belongs to medium rank coal with a primary fractured structure; The concept of "controlling near and expanding far" large-scale volume fracturing technology proposed based on this has been successfully implemented and achieved breakthrough progress. Based on practical situations, analyze the fracturing construction curve, clarify relevant reservoir and engineering parameters, analyze the crack propagation effect, and complete a comprehensive evaluation of the applicability of typical measures and well processes; And combined with long-term production tracking, clarify the characteristics of deep coalbed methane backflow and production after well pressure, providing experience and basis for effective utilization of deep coalbed methane in the later stage.

Keywords: Volume fracturing · Deep coalbed methane · Cleavage · Taiyuan Formation

1 Introduction

In the early stage, the development of coalbed methane was concentrated in the middle and shallow layers, and the first commercial Yanchuan South coalbed gas field with a depth of 1500 m was built in East China. However, 2000 m has always been a prohibited area for exploration and development. In the past two years, China has gradually made breakthroughs in the development of deep coalbed methane. Several horizontal wells of

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China National Petroleum Corporation (CNPC) have achieved daily gas production of over 100000 m^3 per day (with a daily gas production of 101000 m^3 from wells 6 - 7 and 01/02 in the Daji block, and 98000 to 112000 m^3 from wells 14 - 5, which is expected to become a new field for natural gas growth [1–6].

Sinopec has also rapidly carried out exploratory work in the field of deep coalbed methane. In recent years, North China Oil and Gas Company has carried out fracturing development of multiple coalbed methane wells. Some single wells have achieved certain breakthroughs, with a large number of explorations and a relatively systematic understanding of the Taiyuan Formation coal seams. Overall, the design concept has gradually been adjusted to "high-strength volume fracturing" [7–9], with significant improvements in fluid and sand strength, achieving breakthroughs in wells WB 1 and D1–567 (Fig. 1).

Fig. 1. Display of micro cracks and cleats in Taiyuan Formation coal seams

2 Physical Properties of Coal Seams in Taiyuan Formation of Daniudi Gas Field

The buried depth of 8 # coal (Tai1 section) in the deep part of Daniudi is 2500–3000 m, with a reservoir temperature of about 90 °C, a vertical stress exceeding 60 MPa, an average thickness of 10 m, an average porosity of 5.6%, a permeability of 0.26 md, and a high gas content (18 m^3/t, with free gas accounting for more than 20% of the total gas content and free gas saturation exceeding 80%). Overall, it belongs to a medium rank coal ($R_o = 0.122–1.65\%$) and a primary fractured structure.

The main components of bright coal and semi bright coal in the Tai1 section are vitrinite and bright coal, with a content of about 70–80%. They are brittle, easily broken, and have a pitch vitreous luster. They have developed internal cracks, cracks, and cleats (1–2 per section), with a linear and banded structure, and are prone to forming complex crack networks. The degree of fragmentation of bright coal and semi bright coal is higher than that of semi dark coal, and cracks are more likely to extend towards bright coal, making the transformation of semi dark coal more difficult [10–12] (Fig. 2).

The coal rock is mainly subject to plastic failure, with an elastic modulus of 6.41–8.27 GPa and an average of 7.59 GPa; The variation range of Poisson's ratio is 0.19–0.25, with an average of 0.228, and the mechanical brittleness index is 0.65. The brittleness index is high, making it easy to form complex crack networks.

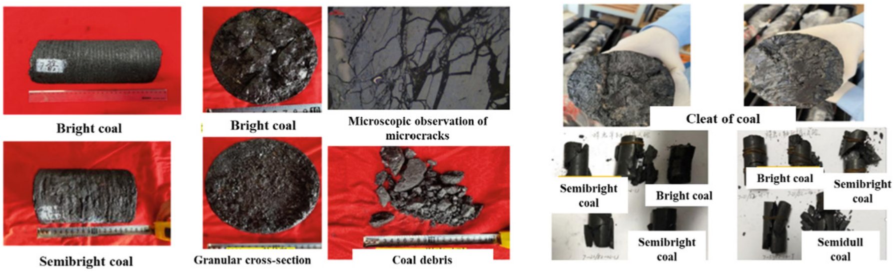

Fig. 2. Schematic diagram of coal seam core

The fracture toughness of Shen8 # is about 0.315 MPa·m$^{0.5}$, and the fracture energy value is about 15.27 MPa·m. From the perspective of fracture toughness, the fracture toughness of Taiyuan Formation 8 # coal is relatively small, easy to fracture, with strong fracture property, and easy to fracture (Daning Jixian fracture toughness 3.4); According to the vertical logging results of the pilot hole of Well YM1HF, a 10 m limestone is developed in the upper part of the target layer, which has a good stress shielding effect. The lower floor is developed with 12 m complex sandstone (carbonaceous mudstone, argillaceous mudstone), with strong heterogeneity and average stress shielding effect. The difference stress between the roof and the floor is 6–10 MPa and 4–11.2 MPa, which is beneficial for controlling the height of the crack. The crack tends to expand along the coal seam [13–15].

3 Well Case of Fracturing in Deep Coal Seams

3.1 Analysis of Well S1 Fracturing

Well S1 adopts casing fracturing, with displacement of 12 m^3/min, liquid consumption of 2036 m^3, sand addition of 133.5 m^3, failure pressure of 36.8 MPa, and pump shutdown pressure of 41.4 MPa. From the operation, the 8 # coal seam has strong fracturing ability, and there is significant room for improvement in sand addition strength (Figs. 3 and 4).

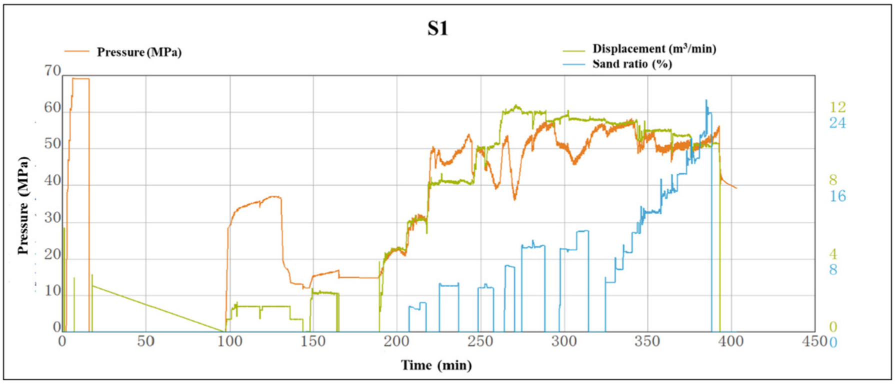

Fig. 3. Fracturing Curve

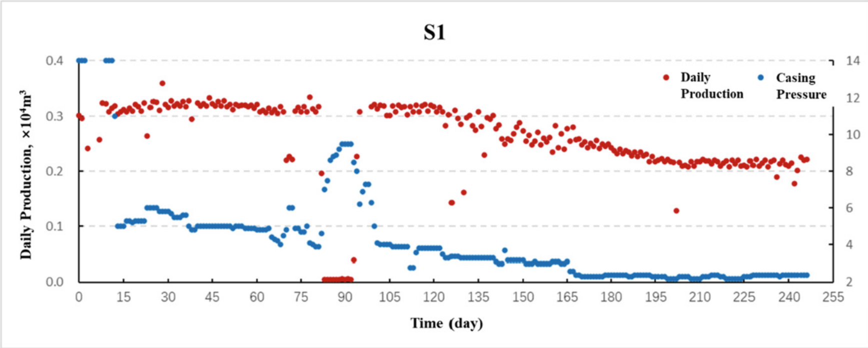

Fig. 4. Production after fracturing

As of May 1, 2023, the accumulated gas production has reached 611000 m^3, with an average daily gas production of 2592 m^3/d and an average daily water production of 4.63 m^3/d. The operation and production of this well has verified that the Tai1 formation has stable production capacity. Increasing the intensity of transformation has the potential to further unleash production capacity.

3.2 Analysis of Well D1–567 Fracturing

Referring to the successful design ideas of Daning Jixian and Yanchuan South, "high-performance (volume, scale, displacement)" design idea is adopted. To verify the reliability of the design concept for large volume fracturing, wide-area electromagnetic and ground micro-seismic monitoring of fracture morphology were used.

Well D1–567 completed with sand addition of 1110 m^3, liquid volume of 10090 m^3, operation displacement of 20 m^3/min, operation pressure of 33–62 MPa, and pump shutdown pressure of 26.8 MPa. Under the high displacement mode, the crack extension is smooth, and there is room for further optimization of design parameters in the later stage.

Half crack length is 296–309 m by wide area electromagnetic method (214–226 m by micro-seismic method). There are three secondary cracks that extend towards the periphery of the wellbore, with a higher density around the wellbore. Large displacement and liquid volume promote the extension of fracture length and the complexity of fractures, which is significantly different from sandstone reservoirs.

Wide-area electromagnetic method proves that in the early stage of fracturing, the main fractures are developed. In the middle and later stages, the width of the fractures is further increased and extended towards the periphery of the wellbore, increasing the complexity of the fractures and communicating more cleats and secondary fractures. Micro-seismic and wide-area electromagnetic monitoring show that after 300 min, the increase in fracture volume was relatively small (Fig. 5).

Dipole acoustic wave was used to test the fracture height after operation. The test height is 34 m, extending up and down by 7.6–8.6 m respectively. This indicates that: (1) selecting the perforation section, using pre-acid and small displacement variable displacement can effectively control the fracture height; (2) The Yang's modulus of the

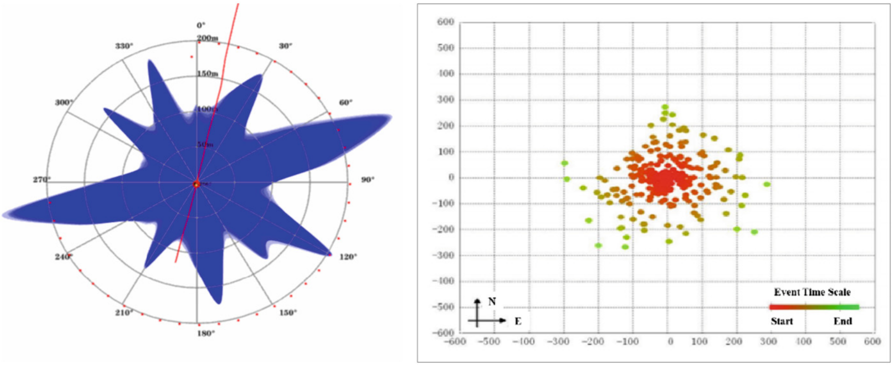

Fig. 5. Wide-area electromagnetic method and micro-seismic monitoring results

top and bottom plates is high, and cracks extend to weak interfaces (with low shear strength), resulting in displacement discontinuity and preventing cracks from extending to the interlayer; (3) Compared to the upper limestone layer, cracks are more likely to extend towards the lower sandstone and mudstone (Fig. 6).

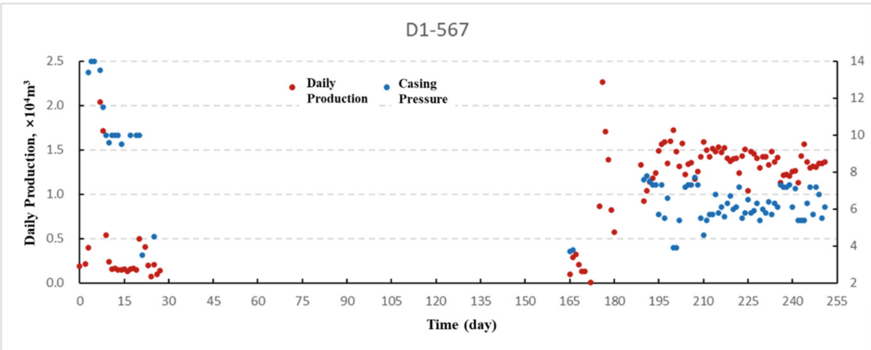

Fig. 6. Production after fracturing

The casing pressure of Well D1–567 remained stable. Up to May 1, 2023, the accumulated gas production was 977000 m^3, with an average daily gas production of 10279 m^3/d and an average daily water production of 8.35 m^3/d. The operation of this well has verified that large-scale volume fracturing can effectively release production capacity. At the same time, through volume fracturing, the gas-liquid ratio has significantly increased compared to Well S1, and the casing pressure has also increased.

3.3 Analysis of Well YM1HF Fracturing

According to DST test data of vertical wells in this area, the average pressure coefficient of Tai-1 section is 0.91, and the average temperature gradient is 2.64 °C/100 m. Taking a vertical depth of 2871 m in the horizontal section, the formation pressure of Well YM1HF is calculated to be 26.12 MPa and the formation temperature is 80.79 °C.

The completed drilling body of YM1HF well is 4090 m, with a vertical depth of 2881.74 m. The actual drilling horizontal section is 1030.00 m long, and the coal seam (gas bearing) section is 854.00 m long. The coal seam (gas bearing) drilling rate is 82.91%. The total hydrocarbon display is the highest at 93.314%, the lowest at 0.539%, and the average at 31.63%. A 10 m thick limestone is developed in the upper part of the Tai1 coal seam; The development of 12 m sandstone on the bottom plate is relatively stable.

1) Fracturing Design Optimization

According to the monitoring of fractures in Well D1–567, when the liquid volume is around 4000 m^3, the extension of the fracture length slows down. Therefore, the single stage liquid volume of fracturing fluid in Well YM1HF is controlled at around 4200–4500 m^3. According to the comparison of sand liquid ratio and sand adding strength between typical coalbed methane wells and D1–567 wells, the comprehensive sand liquid ratio is controlled at around 11–12%. Based on the compressibility evaluation and fracturing segmentation, the sand adding amount for each layer is 450–550 m^3.

Due to the development of cracks in coal seams, the expansion of cracks in coal seams is extremely complex, presenting a large number of irregular cracks and microcracks. Multi particle size composite proppant system is used to fill cracks of different widths. The proportion of 70/140 mesh is increased gradually to ensure the strength of sand addition.

The YM1HF well adopts a design concept of higher strength sand addition, increasing the net pressure to 14–18 MPa. Especially in the limestone section, the displacement of 16–24 m^3/min is required to meet the demand of sand adding strength. The fracturing of this well adopts complex fracture network volume fracturing.

Bright coal has good compressibility (compressibility index 80–85%), semi bright and semi dark coal has medium compressibility (compressibility index 51.7–69.3%), and limestone has poor compressibility (compressibility index 32.2%). The Class III reservoir is a limestone section with high Young's modulus and difficult crack extension, and the fracturing is located at a stress concentration point. Class II reservoirs are divided into 1–8 sections. Based on the length of the segmented Sects. (55–80 m) and the different lithology encountered during drilling in each section (semi bright coal, semi dark coal, dim coal, and mudstone), 2–3 clusters of fracturing are optimized with a cluster spacing of 14–17 m, a construction scale of approximately 390–460 m^3, and a construction displacement of 16–20 m^3/min. Reducing the interval between sections to reduce the number of clusters and increase the net pressure inside the fractures is used to achieve full reservoir transformation up and down. The main body of Class I reservoir is developed with bright coal, which has developed fractures and cleats. In order to fully stimulate this type of reservoir, 2–4 clusters of fracturing are optimized based on drilling conditions, with cluster spacing of 17–22 m and scale of around 500–650 m^3. The construction displacement is 18–20 m^3/min. By appropriately enlarging the segment spacing and increasing the number of clusters, the displacement is increased. By using induced stress between clusters to reduce the stress difference between the two directions, a complex fracture network is formed to fully stimulate bright coal. Fracturing 13 stages and 37 clusters in this well.

2) Analysis of Fracturing Operation

The total liquid inflow is 55135.2 m^3. The total amount of sand is 6614 m^3. The comprehensive sand ratio is 12.06%. The specific statistics are shown in the table below (Table 1):

Table 1. Statistical of Fracturing Materials for Well YM1HF

	Design	Actual		Design	Actual
Low viscosity, m^3	7632	2760	70/140 Quartz sand, m^3	2885.1	2946.9
Middle viscosity, m^3	40170	41569	40/70 Quartz sand, m^3	2609.5	2627.5
High viscosity, m^3	5950	10537	30/50 Ceramsite, m^3	897.2	917.6
Acid, m^3	300	270	30/50 Coated sand, m^3	65	70
Liquid nitrogen, m^3	457	496	40/70 Tracer, t	52	52

In terms of liquid volume usage, due to scheme adjustments, the type of liquid volume has been adjusted (approximately 5000 m^3 adjusting from low viscosity to high viscosity, with a greater emphasis on the formation of main fractures).

The wide area electromagnetic method was used to monitor the morphology of fractures, with an average half fracture length of 204 m and a bandwidth of 92 m for 13 fractured stages. The transformation of the volume fracture network was achieved, and the bandwidth exceeded the expected interval, demonstrating the development of cleats and microcracks in the coal seam (Fig. 7).

The 4th, 6th, 12th, and 13th stages all experienced a sudden drop in pressure during the fracturing process. Except for the 12th section, the pressure in the remaining sections slowly rebounded afterwards. It is believed that cracks penetrating the bottom plate (sandstone and mudstone, with lower stress than the top plate) cause a sudden drop in pressure. The net pressure during construction exceeds 10 MPa, which exceeds the stress difference between the reservoir and the top and bottom plates (Fig. 8).

3) Analysis of Production Status

After drilling and milling the bridge plugs, the converted daily gas production and casing pressure have significantly increased. Accumulated backflow is about 1000 m^3 of gas, with a backflow ratio of about 1.8%. As of now, the maximum converted daily gas production has exceeded 100000 m^3 per day (not connected to pipelines), and the casing pressure has gradually stabilized since 4.12, while the gas volume still maintains a growth trend. After connecting to the pipeline, the average daily gas production is 63649 m^3/d, and the average daily water production is 9.04 m^3/d. Compared to Well D-567, the gas-liquid ratio of segmented volume fracturing in horizontal wells has further increased significantly.

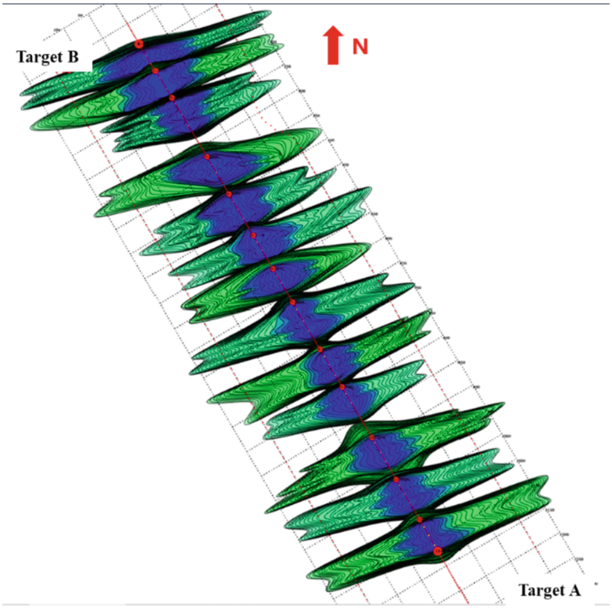

Fig. 7. Monitoring Results of Cracks in Well YM1HF

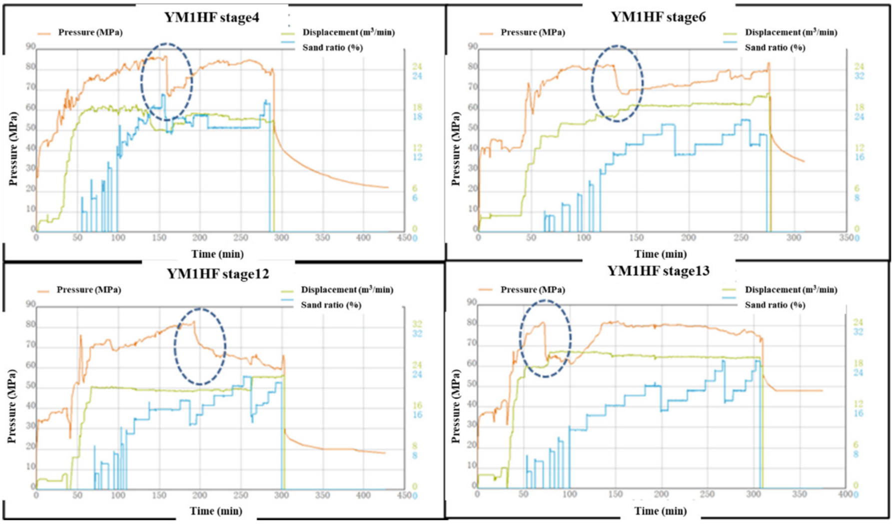

Fig. 8. Fracturing curve for stages of Well YM1HF

4 Comparative Analysis of Fractured Wells

The target reservoir of the three measure wells is the Tai1 coal seam, and the geographical distance is similar (well spacing does not exceed 5 km). Considering the stability of coal seam distribution, theoretically, the construction characteristics of the three wells should be consistent; But the actual situation is not like this.

Considering the insufficient pressure drop duration after some construction well section measures, the actual formation closure stress was not obtained due to the failure to reach the crack closure time point. Therefore, the average value of the actual measured closure stress gradient in the upper and lower sections of the analysis layer is taken as the corrected closure stress gradient, and then the corrected instantaneous net pressure after pump shutdown is calculated (the pressure drop data of Well S1 is not measured, and the closure stress gradient is taken as the average value of the corrected closure stress gradient in each section of Well D1567 + YM1HF).

From the perspective of correcting the closed stress gradient, the differences between each well and section are relatively small, fluctuating between 0.017 and 0.021 MPa/m, and the value range is relatively reasonable. However, there are significant fluctuations in the extended stress gradient and the instantaneous net pressure when the pump is stopped, especially in the differences between the Shi1 and D1–567 wells and YM1HF (Fig. 9).

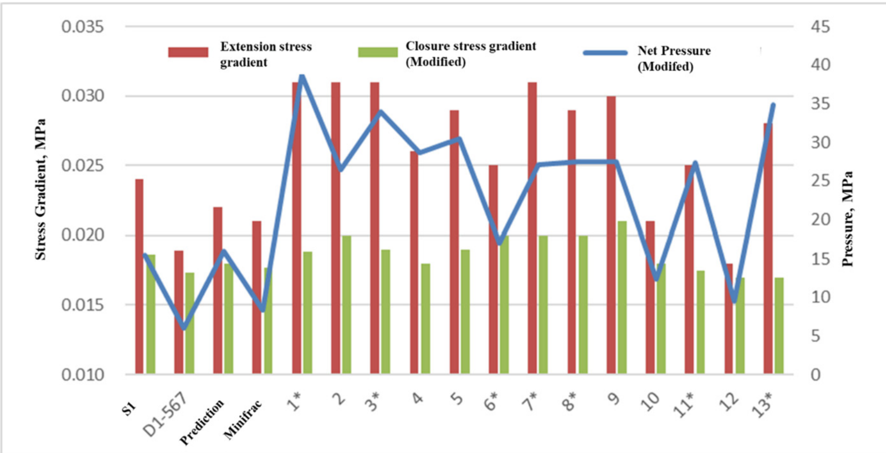

Fig. 9. Statistics of well characteristics

Through statistical analysis of the instantaneous net pressure (corrected) and extended stress gradient values of each measure well section, it can be seen that there is a significant linear relationship between the two parameters. The regression coefficient r^2 is approximately 0.8, indicating a strong correlation between the two parameters (Fig. 10).

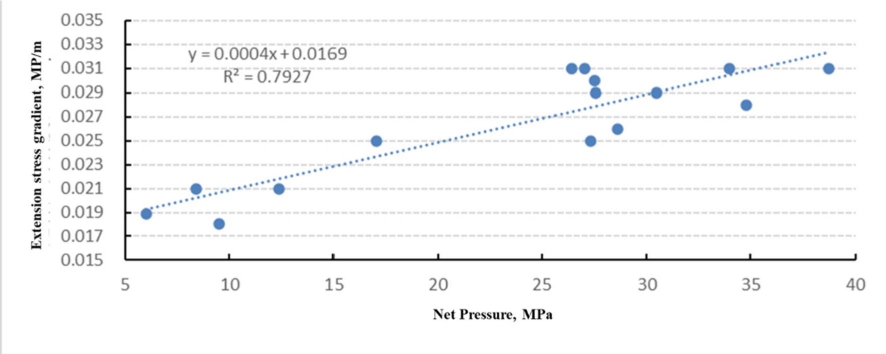

Fig. 10. Relationship between instantaneous net pressure and extended stress gradient

By comparing the fracturing curves of each well section, it is believed that the biggest difference in engineering parameters between S1, D1–567, and YM1HF is the speed of displacement increase. From this perspective, analyze the displacement rate of each well section and calculate the correlation coefficients between various parameters, as shown in the table below (Table 2).

Table 2. Discharge lifting duration of each well section and statistics of engineering parametric statistics

Displacement	S1	D1-567	Mini frac	1	2	3	4	5	6	7	8	9	10	11	12	13	Co-NP	Co-ESG
16-20		9	7										28	8	7	66	0.715	0.737
12-16		19	6	8	137		10	35	26	9	13	12	6	10	6	5	0.099	0.336
10-12	15.4	17	3	4	10	5	4	2	5	8	3	15	6	1	1	1	-0.314 ↑	-0.046 ↑
8-10	29	15	3	1	6	5	3	5	3	4	5	1	1	1	1	1.2	-0.333 ↑	-0.194 ↑
4-8	26.5	101	9	4	2	4	1	3.1	4	2	3	7	8	1	9	2.8	-0.552 ↑	-0.511 ↑
0-4	3.5	47	12	2	22	8	6	0.9	2	2	4	2	2	6	2	2	-0.424 ↓	-0.325 ↓
Net Pressure(Modifed)	15.44	5.99	8.39	38.74	26.39	33.99	28.59	30.49	17.04	27.04	27.54	27.49	12.39	27.29	9.49	34.79		
Extension stress gradient	0.024	0.0189	0.021	0.031	0.031	0.031	0.026	0.029	0.025	0.031	0.029	0.03	0.021	0.025	0.018	0.028		

There is a significant correlation between the duration of displacement increase (i.e. the rate of displacement increase) and the net pressure and extension stress gradient; The overall pattern is that the higher the rate of displacement increase, the higher the net pressure and extension stress gradient, which is in line with common sense;

The lifting speed of 0–8 m^3/min has the most significant impact on the net pressure and extension stress gradient, indicating that the coal seam has a certain sensitivity to loading speed. To avoid excessive construction pressure, it is recommended to control the loading rate in the displacement range of 0–10 m^3/min.

According to the statistics of the increase of the discharge between zones, the following understandings are summarized: the influence of the 4–8 m^3/min interval is more significant, and from the perspective of controlling the construction pressure, the speed of the increase of the discharge in this interval should be reduced; The rate of displacement increase above 12 m^3/min is negatively correlated with the extension stress gradient and net pressure. The increased rate of displacement increase is actually beneficial for controlling construction pressure, especially in the high displacement range of 16–20 m^3/min where the regularity is very significant (the regularity of high displacement is stronger than that of low displacement).

5 Conclusion

(1) There is a significant correlation between the duration of displacement increase (i.e. the rate of displacement increase) and the extension stress gradient, and there is a certain sensitivity of loading speed in coal seams;
(2) The lifting speed of 4–8 m^3/min has the most significant influence on the extension stress gradient. From the perspective of controlling the construction pressure, the displacement lifting speed in this section should be reduced; The increase rate of displacement above 12 m^3/min is negatively correlated with the extension stress gradient, and the regularity of high displacement is stronger than that of low displacement;
(3) Through the iteration of fracturing technology, larger scale and higher displacement construction is conducive to unleashing the production potential of coal seams. The complex fracture network volume fracturing process system of "controlling near and expanding far", achieving "saturated sand addition and effective support", has applicability in deep coal and rock reservoirs; At the same time, the proportion of water production decreases after larger scale production, and the water production rate of deep coal seams is lower than expected.

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