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Research on Segmented Hydraulic Fracturing Technology for Directional Long Boreholes in Coal Mines

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Abstract: Hydraulic fracturing in coal mines is an advanced technology that reduces pressure, increases permeability, and effectively improves the effectiveness of coal seam gas extraction. In order to improve coal seam gas extraction and effectively prevent gas disasters in Daning Coal Mine, the segmented hydraulic fracturing process and its crack propagation law were analyzed. The directional long borehole segmented hydraulic fracturing technology in the coal mine was applied on-site in Daning Coal Mine. The research results show that the segmented hydraulic fracturing process can be divided into four stages: system water filling, system pressurization, crack propagation, and system pressure relief. Under the same extraction time conditions, the average increase in pure drilling extraction after hydraulic fracturing at the Xida 1-05 drilling site of Daning Coal Mine is 30%.

Keywords: Coal Mines; Directional Long Drilling; Segmented Hydraulic Fracturing; Crack Propagation; Extraction.

1. Introduction

China is a major coal resource country and one of the countries in the world with severe coal mine disasters and frequent accidents. With the increase of coal mining depth and intensity, coal and gas outburst problems have become increasingly serious, and have become one of the main problems that seriously threaten the safety production of mining areas [1-2]. With the development of gas control technology in recent years, in addition to conventional drilling gas extraction, technologies aimed at increasing permeability of coal seams and improving gas extraction efficiency are constantly emerging. The commonly used methods for enhancing coal seam permeability currently include hole drilling, deep hole pre splitting blasting, hydraulic punching, and hydraulic fracturing [3-7]. Hydraulic fracturing technology has obvious advantages in the above-mentioned types of permeability enhancement measures [8-10]. Hydraulic fracturing is a measure that uses water as the driving force to make coal fractures unobstructed. Hydraulic fracturing permeability enhancement technology is the process of injecting high-pressure water into coal seams through drilling holes. When the speed of water injection far exceeds the natural water absorption capacity of the coal seam, the pressure of high-pressure water entering the coal seam gradually increases due to the increase in flow resistance. When the pressure of high-pressure water exceeds the rock pressure of the coal seam, the original closed cracks in the coal seam will be opened to form a new gas circulation network, and the permeability of the coal seam will increase. When the pressed liquid is discharged, the opened cracks create favorable conditions for the flow of coal seam gas.

Shanxi Yamei Daning Energy Co., Ltd. (referred to as "Daning Coal Mine") has a high original gas content and pressure in the coal body, and the coal seam has good solidity and permeability coefficients. All coal seam extraction boreholes are constructed using directional drilling machines, with high drilling trajectory accuracy and good drilling completion rate. Therefore, hydraulic fracturing and permeability enhancement technology is suitable for the prevention and control of gas disasters in the mine and can obtain good technical support.

2. Overview of the Experimental Mine

The Daning Coal Mine is located approximately 16km north of Yangcheng County, Jincheng City, Shanxi Province. The mining area is 38.8225km^2, and the mining depth ranges from 620m to 360m. The production scale is 4.00Mt/a. The main coal seam in Daning Coal Mine is No.3 coal, with a thickness of 2.21-6.97m and an average of 4.45m, which belongs to the thick coal seam. The apparent density of the coal seam is 1.36t/m^3, the true density is 1.47t/m^3, and the Proctor hardness coefficient is about 1.48. The mine structure is simple, with a burial depth of 256-288m. The dip angle of the coal seam is generally less than 9 °, and it is a nearly horizontal thick coal seam. The floor elevation is+480-580m. According to the Reply on the Appraisal Results of Gas Level and Carbon Dioxide Emission in Jincheng City's Mines in 2012, the absolute gas emission of Daning Coal Mine in 2012 was 456.21m^3/min, with a relative emission of 47.09m^3/t, an absolute carbon dioxide emission of 19.26m^3/min, and a relative emission of 1.99m^3/t. The approved level is an outburst mine, and the No.3 coal being excavated belongs to the gas outburst coal seam.

The Xida 1-05 drilling site was selected as the experimental area for this segmented hydraulic fracturing. The thickness of the coal seam in this area ranges from 2.8m to 4.6m. The coal (rock) strata in the area have relatively small changes in attitude, with dip angles ranging from 280 to 320 ° and dip angles ranging from 2 ° to 6 °. The main roof is composed of siltstone and medium fine sandstone, with a thickness of 12.42 to 16.43m. The direct roof is composed of fine sandstone, with a thickness of 7.4 to 8.8m. The direct bottom is composed of mudstone or siltstone, with a thickness of 0.6 to 1.2m. The main bottom is composed of fine sandstone, with a thickness of 16.7 to 20.8m. Four directional long boreholes were constructed at the Xida 1-05 drilling site, including two fracturing boreholes and two comparative inspection boreholes. Fracturing drilling involves four stages of hydraulic fracturing with a single open hole, with the farthest fracturing point located 490m away from the orifice. The pure duration of fracturing is 564 minutes, with a total injection volume of 160.8m3 and a peak fracturing pressure range of 26-37.5 MPa.

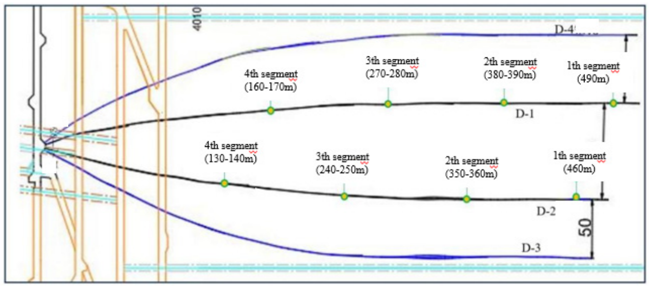

Figure 1. Hydraulic fracturing construction design for Xida 1-05 drilling field

Table 1. Drilling construction situation

Number	Hole length (m)	Number of fracturing sections	Total fracturing time (min)	Total pressure injection water volume (m^3)	Range of single stage fracturing time (min)	Peak pressure range (MPa)	Range of single end injection water volume (m^3)
1#	501	4	289	81.4	56-74	27.6-32.5	17.5-24.2
2#	474	4	275	79.4	60-72	31.4-37.5	19-23.5
3#	474	/	/	/	/	/	/
4#	516	/	/	/	/	/	/
Total	1965	18	564	160.8	/	/	/

3. Research on Segmented Hydraulic Fracturing Technology

During the segmented hydraulic fracturing process, the dynamic changes of the pressure time curve fully record the interaction relationship between high-pressure water and the target rock layer, reflecting the initiation, development, and expansion of hydraulic fractures in the formation. This section takes the fracturing pressure time curve of the third section of hole 1 # as an example (as shown in Figure 2) to explain and introduce the fracturing process and crack propagation.

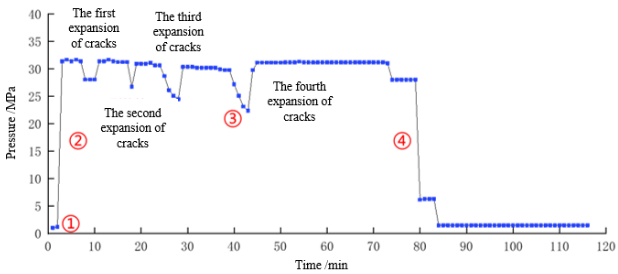

Figure 2. Fracturing pressure time curve of the third section of 1# hole

From the Figure 2, a typical water pressure curve can be divided into the following four stages:

(1) First stage (system water filling). This stage is the high-pressure pipeline, packer, and internal water filling stage of the drilling hole. The pressure value of the entire fracturing pump injection system in this stage is 0MPa, until the water filling is completed after pumping for a period of time. The water filling stage takes 2 minutes.

(2) Second stage (system boosting). After the hydraulic fracturing pump system is filled with water, the hydraulic fracturing pump group continues to pressurize and inject water, and the water pressure value of the target fracturing section rapidly increases to 31.3MPa.

(3) Third stage (crack propagation). After the internal water pressure of the borehole reaches its peak stage, the water pressure overcomes the effect of geostress, causing the inner wall of the borehole to crack and expand into a crack space. The crack expansion leads to a decrease in the water pressure value. Due to the continuous pressure injection of the fracturing pump group, high-pressure water quickly fills the crack space, and the water pressure value increases. Under the interaction between high-pressure water and geostress, hydraulic fractures continuously generate, develop, and expand, which is manifested as significant fluctuations in the water pressure curve. In the later stage of hydraulic fracturing construction, the main hydraulic fractures have basically completed their development and expansion. With the continuous filling of high-pressure water, network like branching cracks is generated around the main hydraulic fractures. At this time, the crack generation and expansion rate are relatively uniform and slow, and the pumping rate and crack network expansion rate reach a dynamic equilibrium state, manifested as a relatively stable state in the latter half of the water pressure curve.

(4) Fourth stage (system pressure relief). After the fracturing operation is completed, turn off the high-pressure pump group, open the pressure relief valve at the orifice to drain and release pressure, and the water pressure value rapidly drops to 0MPa.

Hydraulic fracturing technology uses high-pressure fluids to break down the overall mechanical properties of coal and rock masses by drilling, holding pressure, and creating fractures in coal and rock masses, improving the hard roof and achieving the goal of pressure relief and erosion prevention. Therefore, in the entire engineering application, the expansion of hydraulic fractures determines the final hydraulic fracturing construction effect. According to the principle of hydraulic fracturing technology, during the fracturing process, as the high-pressure pump group continuously pressurizes and injects water, the coal and rock masses around the borehole undergo deformation and softening under the action of high-pressure water, forming cohesive cracks. In turn, high-pressure fluid drives the further development and expansion of cohesive cracks, forming a real fracture space.

As shown in Figure 2, the formation of hydraulic fractures is manifested by the jumping behavior of the water pressure curve. This jumping phenomenon is defined as pressure drop. The data of this fracturing construction is analyzed, and the hydraulic fracturing construction effect is summarized and characterized using pressure drop parameters. The expansion of hydraulic fractures includes the extension of hydraulic main fractures and the development and formation of micro fracture networks on this basis. The expansion of hydraulic main fractures was identified as the main focus of the analysis of the hydraulic fracturing effect in directional long drilling. Therefore, the construction data of hydraulic fracturing were analyzed and statistically analyzed, and the number of significant pressures drops above 3MPa is summarized in Table 2.

Table 2. Summary of pressure drop above 3MPa in directional long boreholes

Number	1 segment	2 segment	3 segment	4 segment	Total
1#	1	2	2	4	9
2#	2	2	1	1	6

According to Table 2, during the hydraulic fracturing construction of directional long drilling, there were 9 instances of significant pressure drop above 3MPa in hole 1 and 6 instances in hole 2, with a total of 15 instances of significant pressure drop above 3MPa in both holes. From 1# hole to 2# hole, the statistical results of pressure drop above 3MPa show a trend of first increasing and then decreasing. This is because at the beginning of fracturing construction, the overall mechanical properties of the roof are relatively intact, and there are fewer primary cracks inside the coal rock mass. After the completion of fracturing construction in hole 1 #, there are a large number of hydraulic cracks in the coal rock mass, and the mechanical properties of the roof are weakened. However, due to the small amount of fracturing construction, the roof still has a certain strength. After the fracturing construction of 1# hole is completed, the overall integrity of the roof is effectively reduced, the coal rock structure is modified, and the mechanical properties are greatly reduced. Therefore, during the fracturing construction of 2# hole, the obvious pressure drop phenomenon is reduced compared to before.

4. Analysis of Fracturing Effect Inspection

The 1# and 2# fracturing boreholes at Xida 1-05 drilling site were completed on August 18 and 23, 2023, respectively, and the fracturing work for the two boreholes was completed from August 26 to 27, 2023. The drilling construction for the 3 #and 4# comparative boreholes was completed on September 3 and September 10, 2023.

4.1. Comparison of Pumping Data Before and After Fracturing Drilling

Considering the influence of the attenuation coefficient of drilling extraction volume, the average extraction volume data per minute for one month after drilling fracturing was compared with the initial average extraction volume data per minute before drilling fracturing, as shown in Table 3. From the Table 3, it can be seen that by comparing the pre fracturing and post fracturing results of a single hole, the initial pure extraction volume of a single hole can increase by more than one time after fracturing, and the minimum can also reach 0.3 times. Within a month, the average extraction volume per minute of a single hole can be increased by 20%.

Table 3. Comparison of pumping data before and after fracturing drilling

Date	1# hole				2# hole				Remarks
	Negative pressure (KPa)	Concentration (%)	Mixing amount (m^3/min)	Pure quantity (m^3/min)	Negative pressure (KPa)	Concentration (%)	Mixing amount (m^3/min)	Pure quantity (m^3/min)	
2023/8/25	15.3	82	1.3	1	15.3	87	1.3	1.2	Before fracturing
2023/9/1	19.4	82	2	1.6	19.4	90	1.8	1.6	After fracturing
2023/9/8	20.5	86	2.2	1.9	20.5	90	1.6	1.5	After fracturing
2023/9/15	18.3	71	2.9	2.1	18.3	78	1.5	1.1	After fracturing
2023/9/22	28.6	82	1.2	1	28.6	85	1.2	1.1	After fracturing
2023/9/29	32.6	79	1.5	1.2	32.6	82	1.2	1	After fracturing
Average	/	/	/	1.56	/	/	/	1.26	

4.2. Comparison of Fracturing Drilling and Comparison Drilling Extraction Data

Based on the data statistics of the past two months, considering the different completion times and statistical measures of drilling, the fracturing drilling and comparison drilling were analyzed according to the average extraction volume per minute of drilling, as shown in Table 4. From the Table 4, the pure gas extraction volume of the 1# fracturing drilling hole is 1.20.8~2.1m^3/min, with an average of 1.36m^3/min. The pure gas extraction volume of 2# fracturing drilling hole is 0.8-1.6m^3/min, with an average of 1.22m^3/min. The gas extraction purity of the 3# comparison borehole is 0.5-1.4m^3/min, with an average of 1.05m^3/min. The gas extraction purity of the 4# comparison borehole is 0.5-1.7m^3/min, with an average of 0.91m^3/min. By comparing the extraction data of the past two months, it was found that the hydraulic fracturing drilling with the same extraction time increased the pure extraction volume by a maximum of 49% compared to normal drilling, the lowest by 16%, and an average increase of about 30%.

Table 4. Comparison of cumulative extraction data between fracturing and conventional drilling

Data	1# hole		2# hole		3# hole		4# hole	
	Concentration (%)	Pure quantity (m^3/min)	Concentration (%)	Pure quantity (m^3/min)	Concentration (%)	Pure quantity (m^3/min)	Concentration (%)	Pure quantity (m^3/min)
2023/9/1	82	1.6	90	1.6	/	/	/	/
2023/9/8	86	1.9	90	1.5	89	0.9		/
2023/9/15	71	2.1	78	1.1	29	0.5	82	1.7
2023/9/22	82	1	85	1.1	74	1.2	84	0.5
2023/9/29	79	1.2	82	1	70	1	81	0.7
2023/10/6	87	0.8	90	0.8	82	1.1	86	0.6
2023/10/13	87	1.2	90	1.8	85	1.4	81	1.2
2023/10/20	81	1.2	8.3	1.1	76	1.3	74	0.9
2023/10/27	90	1.2	90	1	88	1	83	0.8

5. Conclusion

(1) The hydraulic fracturing process can be divided into four stages: system water filling, system pressurization, crack propagation, and system pressure relief.

(2) Through on-site testing of directional long borehole segmented hydraulic fracturing at the Xida 1-05 drilling site of Daning Coal Mine, the gas extraction pure volume of the 1# fracturing borehole was 0.8-2.1m^3/min, with an average of 1.36m^3/min. The pure gas extraction volume of 2# fracturing drilling hole is 0.8-1.6m^3/min, with an average of 1.22m^3/min. And the gas extraction purity of the 3# comparison borehole is 0.5-1.4m^3/min, with an average of 1.05m^3/min. The pure gas extraction volume for 4# comparison drilling is 0.5-1.7m^3/min, with an average of 0.91m^3/min. The hydraulic fracturing drilling with the same extraction time has a maximum increase of 49% in pure extraction compared to normal drilling, a minimum increase of 16%, and an average increase of about 30%.

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