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Research on the Effective Extraction radius of Directional Long Boreholes for Coalbed Methane Extraction Based on Gas Extraction Quantity Measurement

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Abstract: In order to solve the problems of low utilization rate of coalbed methane and difficult gas control in the working face caused by the difficulty of ordinary drilling construction for gas extraction in a high gas mine, a study was conducted on the effective extraction of coalbed methane using directional long drilling in the 2212 working face of a certain coal mine. Through on-site experimental investigation and theoretical analysis, the effective extraction radius of directional long boreholes in the working face was calculated under different pre extraction times, providing a scientific basis for the rational design of directional long boreholes for coalbed methane extraction.

Keywords: Coal Mine; Directional Long Drilling; Coalbed Methane Utilization; Extraction Radius; Gas Extraction Volume; Sampling Meets the Standard.

1. Introduction

Coalbed methane, as a high calorific value clean energy, is a high-quality industrial, chemical, power generation, and residential fuel. The development and utilization of coalbed methane can reduce greenhouse gas emissions and assist in energy conservation and carbon reduction [1,2]. At the same time, by pre extracting coalbed methane, it can ensure that the gas in the coal seam is fully released and reduce the risk of coal mine safety production. One of the key factors for effectively mining and utilizing coalbed methane is to determine the construction parameters of efficient gas extraction boreholes based on the actual situation on site [3]. By reasonably determining the drilling and extraction radius, the extraction efficiency of a single drilling hole can be maximized, and the number of drilling holes for construction can be reduced. This reduces the cost of coalbed methane development, while ensuring safety and efficiency, achieving cost control and maximizing economic benefits. The investigation of extraction radius helps to more accurately evaluate the recoverable amount of coalbed methane resources, providing scientific basis for the development planning and production capacity prediction of coalbed gas fields.

A certain coal mine is located in Changzhi City, Shanxi Province, with an annual production capacity of 1.20Mt/a. At present, the No.2 coal seam is being mined as a high gas mine with abundant reserves of coalbed methane. There are two sets of surface gas generators in the mine, which directly utilize the extracted coalbed methane. Previously, a certain coal mine mainly used ordinary drilling to extract coalbed methane from the No.2 coal seam, with a drilling distance of 3m and a construction length of 90~110m. Due to the thin thickness of the No. 2 coal seam, which varies between 0.8 and 2.0m, it is possible for ordinary drilling to reach a depth of more than 30m during actual construction, and after encountering the rock, it is necessary to retreat from drilling and resume construction. Therefore, a certain coal mine is facing the problem of low efficiency in gas extraction drilling construction, which affects coalbed methane extraction and gas control.

In order to improve the utilization rate of coalbed methane and solve the problem of mining extraction. A certain coal mine research adopts directional long drilling with active control of drilling trajectory to solve the problem of low construction efficiency caused by frequent rock contact during drilling. Therefore, relevant research was conducted on the extraction radius of directional long boreholes in the No. 2 coal seam of a certain coal mine.

2. Experimental Drilling Design and Construction

The 2212 working face is located in the second mining area, mining the No.2 coal seam with an average coal thickness of 1.7m. The maximum original gas content measured in the 2212 working face is 11.4m^3/t, and it is necessary to extract the working face. The working face is equipped with two grooves, namely 2212 machine lane and 2212 air lane, with a length of 1090m and a cut length of 217m. The U-shaped ventilation method is adopted, and the recoverable capacity is 528400 tons with a service life of 0.88 years. The 2212 working face is low in the east and high in the west, with relatively simple geological conditions. According to the overall plan of the mine excavation replacement arrangement and research, directional long boreholes will be constructed within a range of 160m from the original coal body in the north of the 2212 machine roadway in the 2212 working face, which is 428m-588m away from the south return air roadway in the second mining area, to pre extract coalbed methane. At the same time, the extraction radius of the directional long boreholes will be inspected. The experimental area is the original coal body that is not affected by mining, with no structure and a smooth and unbroken roadway. Due to the fact that the gas flow field between directional long boreholes during extraction is a finite source gas flow field [4], over time, the boreholes will interact with each other [5,6]. Therefore, in order to simulate the extraction law under the mutual influence of drilling, 6 groups of drilling holes were arranged in the experimental area with a spacing of 10m, and 5 drilling holes were constructed in each group. The spacing of the drilling holes was 2m, 3m, 4m, 5m, 6m, and 7m, respectively. The length of the experimental drilling holes was 60m, the diameter of the drilling holes was 96mm, the opening height was 1.0m, and the inclination angle was 0~+5 °, which were upward holes. The layout of the extraction drilling holes is shown in Figure 1.

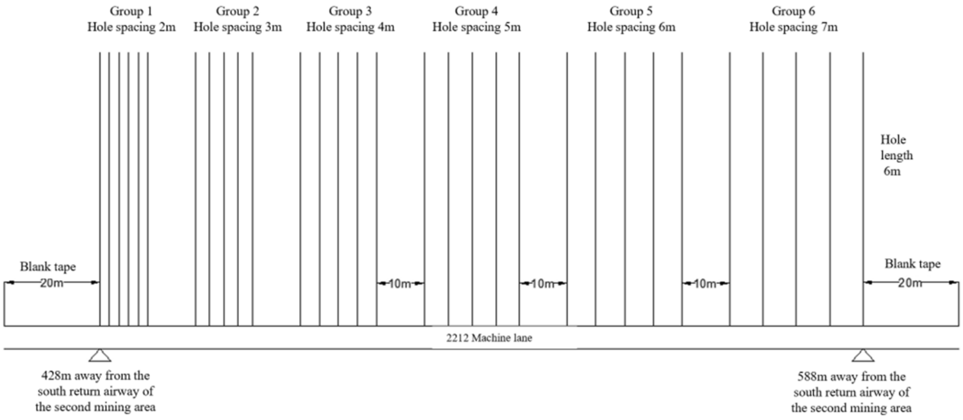

Figure 1. Schematic diagram of drilling layout for radius inspection test of extraction

The completion parameters of directional long drilling test are shown in Table 1. After the completion of the drilling construction, the bag type pressure grouting sealing method is used to seal the hole, with a sealing depth of 15m. The drainage pipe is made of D75mm PVC pipe with safety labels. After sealing, it is connected to the main drainage pipe in a timely manner, and the drainage negative pressure is about 18kPa. Install an orifice plate on the extraction pipe, use an orifice plate flowmeter to record the gas extraction flow rate from the borehole, and measure data including extraction negative pressure, pressure difference, concentration, temperature, etc. Record once a day in the first month after drilling, and once a week in the following two months.

Table 1. Drilling completion parameters for directional long borehole extraction radius

Hole number		Angle with roadway/°	Dip angle/°	Hole depth/m	Spacing/m	Hole number		Angle with roadway/°	Dip angle/°	Hole depth/m	Spacing/m
A	A-1	90	2	61	2	D	D-1	90	2	60	5
	A-2	90	2	33			D-2	90	2	60	
	A-3	90	2	63			D-3	90	2	60	
	A-4	90	1	60			D-4	90	2	52	
	A-5	90	3	40			D-5	90	2	60	
B	B-1	90	0	61	3	E	E-1	90	1	55	6
	B-2	90	3	60			E-2	90	2	60	
	B-3	90	2	60			E-3	90	2	50	
	B-4	90	2	45			E-4	90	2	60	
	B-5	90	2	60			E-5	90	2	60	
C	C-1	90	2	60	4	F	F-1	90	2	60	7
	C-2	90	2	60			F-2	90	2	60	
	C-3	90	2	60			F-3	90	2	60	
	C-4	90	2	60			F-4	90	2	60	
	C-5	90	2	60			F-5	90	2	48	

3. Theoretical Analysis and Calculation of Gas Extraction Radius

3.1. Gas Extraction Law of Drilled Holes with Different Spacing for Gas Extraction

In order to investigate the effect of pre drilling gas extraction, the characteristic parameters characterizing the variation of drilling gas extraction amount over time, namely the initial gas extraction amount of the drilling hole (q_{c0}) and the attenuation coefficient of gas extraction amount (β), were measured. When measuring, the average gas extraction net amount per 100m of boreholes (q_{ct}) is calculated based on the mixed flow rate, mixed concentration, extraction time, and borehole length of gas extracted from each borehole every day, and a measurement array (t, q_{ct}) is formed by combining the extraction time of boreholes (t). The value q_{c0} and β can be obtained through regression analysis using equation 1 based on the (t, q_{ct}) array.

According to extensive research by researchers [7-9], the amount of gas extraction from boreholes (q_{ct}) and the extraction time (t) of boreholes well follow a negative exponential function relationship, as follows:

$$q_{ct} = q_{c0} e^{-\beta t} \tag{1}$$

Where, q_{c0} is initial gas extraction amount from a 100 meter borehole, $m^3/min \cdot hm^{-1}$; q_{ct} is the average gas extraction amount from a 100 meter borehole at extraction time t, $m^3/min \cdot hm^{-1}$; β is attenuation coefficient of drilling gas extraction volume, d^{-1}; t is gas extraction time of drilling holes, d.

By integrating equation 1, the total amount of gas extraction from boreholes within any time t day can be obtained:

$$Q_{ct} = \int_0^t q_{c0} e^{-\beta t} = \frac{1440 \cdot q_{c0}(1-e^{-\beta t})}{\beta} \qquad (2)$$

Where, Q_{ct} is the total amount of gas extraction from boreholes, m^3; Q_{cj} is maximum gas extraction capacity through drilling when t→∞.

In order to obtain the true extraction pattern of drilling groups with different spacing, the average of the single hole extraction pure amount of 5 drilling holes in each group was calculated and converted into the pure amount of gas extraction from 100 meter drilling holes. Then, the relationship between the pure amount of gas extraction from 100 meter drilling holes and time was fitted into a curve. The function relationship between the pure amount of gas extraction, the total flow rate of gas extraction from a 100 meter borehole from drilling groups with spacing of 2m, 3m, 4m, 5m, 6m, and 7m and time is shown in Table 2.

Table 2. The relationship between q_{ct}, Q_{ct} and t with different spacing for extraction

Spacing/m	The relationship between q_{ct} and t	The relationship between Q_{ct} and t
2	q_{ct}=0.0424$e^{-0.028t}$	$Q_{ct} = 2180.81(1-e^{-0.028t})$
3	q_{ct}=0.0546$e^{-0.026t}$	$Q_{ct} = 3026.70(1-e^{-0.026t})$
4	q_{ct}=0.0606$e^{-0.024t}$	$Q_{ct} = 3634.75(1-e^{-0.024t})$
5	q_{ct}=0.0661$e^{-0.023t}$	$Q_{ct} = 4140.92(1-e^{-0.023t})$
6	q_{ct}=0.0679$e^{-0.021t}$	$Q_{ct} = 4652.86(1-e^{-0.021t})$
7	q_{ct}=0.0698$e^{-0.020t}$	$Q_{ct} = 5025.60(1-e^{-0.020t})$

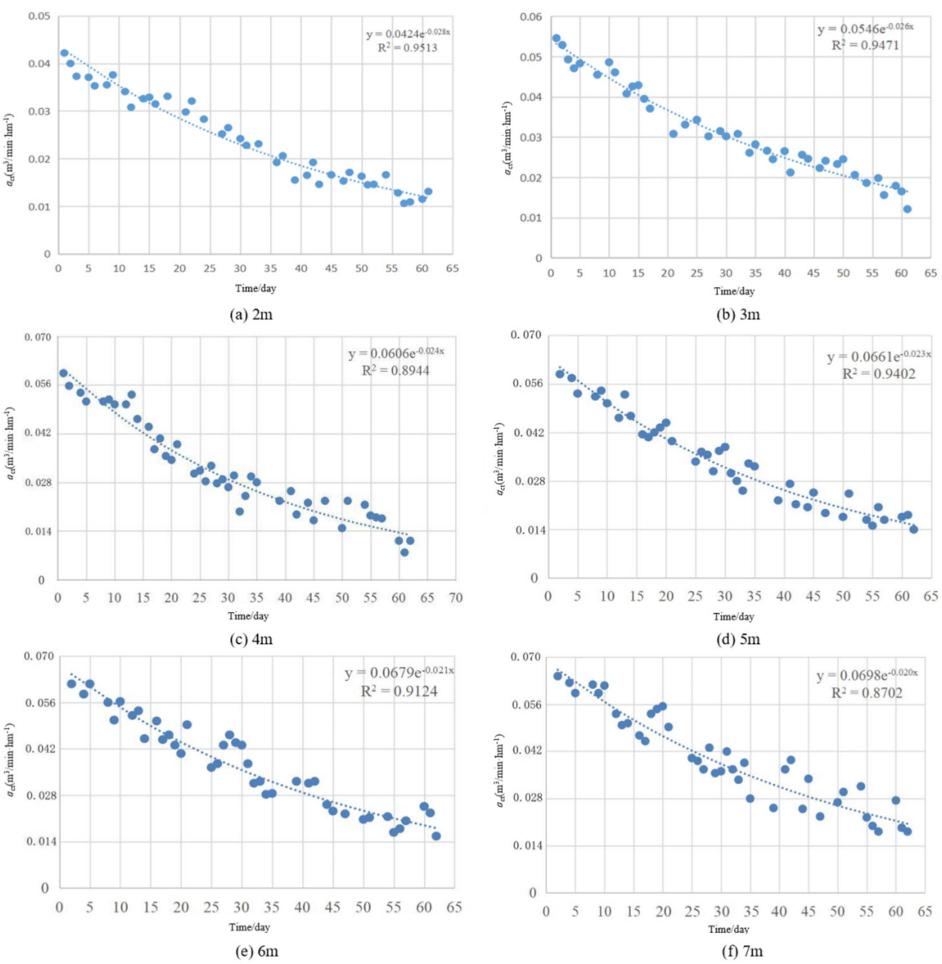

Figure 2. Decay trend chart of gas flow rate per hundred meters with different drilling spacing

According to Table 2, the gas flow rate decreases in a negative exponential relationship with the increase of extraction time. The longer the extraction time, the smaller the gas extraction flow rate. The smaller the spacing between drilling holes for gas extraction, the greater the attenuation coefficient of gas extraction flow. This indicates that under the same area of coal, same extraction time, and same original coal seam gas content conditions, the smaller the spacing between drilling holes, the faster the gas extraction speed, and the faster the decrease in coal seam gas content. The total flow rate of gas extraction from a 100 meter drilling hole increases in a negative exponential relationship with the increase of extraction time. The longer the extraction time, the smaller the increase in the total amount of extraction, and there is a limit to the total amount of extraction [10]. The larger the spacing between drilling holes for gas extraction, the greater the limit value of the total flow rate for gas extraction in 100 meter drilling holes.

3.2. The Relationship between Gas Pre extraction Rate and Time in Boreholes with Different Spacing

The gas pre extraction rate is the main indicator for measuring the effectiveness of drilling pre extraction of coal seam gas. It refers to the ratio of the amount of gas extracted from drilling within a certain range to the coal seam gas reserves within that range under a certain extraction time. It is calculated using the following formula:

$$\eta = \frac{100Q}{L \times l \times M_0 \times r \times W_0} \tag{3}$$

Where, η is pre extraction rate of drilling gas, %; Q is pure gas extracted from a 100 meter borehole within the time of t extraction,m^3; L is drilling control range, m, with drilling layout spacing of 2m, 3m, 4m, 5m, 6m, and 7m respectively; l is the length of the extraction borehole, m, is the flow rate of 100 meters of the borehole, and its value is taken as 100 meters; M_0 is the average coal thickness, m, takes the coal thickness of 2212 working face as 1.7m; r is the density of coal, t/m^3, takes the average apparent density of coal seam 2 as 1.33t/m^3; W_0 is the original gas content of the coal seam is m^3/t, and the maximum measured gas content in the test area is 11.4m^3/t.

According to formula 3, the relationship between gas pre extraction rate and time within the control range under different drilling spacing can be obtained as shown in Table 3 and Figure 3. It can be seen that there is a limit value for the gas pre extraction rate of boreholes with different spacing. It is meaningless to increase the extraction time after reaching a certain pre extraction rate. This is consistent with reality, not that the longer the extraction time, the better, but rather that there is a reasonable economic value that can achieve the extraction effect while saving energy. As the spacing between boreholes increases, the limit pre extraction rate of gas in boreholes decreases. When the gas limit pre extraction rate is lower than the extraction standard value when the spacing between boreholes is further increased for extraction, no matter how long the extraction is carried out, it is impossible to achieve the coal seam extraction standard [11].

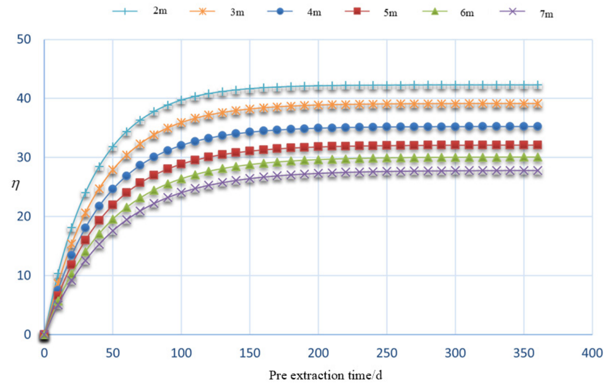

Figure 3. Gas pre extraction rate diagram of boreholes with different spacing

Table 3. The relationship between η and t with different spacing for extraction

Spacing/m	The relationship between η and t
2	$\eta = 42.3041\left(1 - e^{-0.028t}\right)$
3	$\eta = 39.1420\left(1 - e^{-0.026t}\right)$
4	$\eta = 35.2541\left(1 - e^{-0.024t}\right)$
5	$\eta = 32.1308\left(1 - e^{-0.023t}\right)$
6	$\eta = 30.0859\left(1 - e^{-0.021t}\right)$
7	$\eta = 27.8538\left(1 - e^{-0.020t}\right)$

3.3. Determination of Pre extraction Rate under Gas Extraction Standards

The pre extraction rate when gas extraction meets the standard can be calculated based on the residual gas content and original gas content when gas extraction meets the standard, using the following formula:

$$\eta = (W_0 - W_{cy}) / W_0 \tag{4}$$

Where, η is pre extraction rate of drilling gas, %; W_0 is the original maximum gas content of the coal seam is m^3/t, and the maximum gas content in the experimental area is 11.4m^3/t; W_{cy} is the average residual gas content of the coal seam after reaching the standard of extraction, m^3/t.

The residual gas content in the coal seam when the extraction meets the standard is 8m^3/t according to the requirements of a certain coal mine. Therefore, the maximum residual gas content in the coal seam when the extraction meets the standard in the experimental area should be less than 8m^3/t. By incorporating the residual gas content of 8m^3/t into formula 17, the pre extraction rate of coal seam drainage reaching the standard can be calculated as 29.82%.

4. Determination of Effective Extraction Radius

According to the relationship between gas pre extraction rate and time function of drilling holes with different spacing, as well as the gas pre extraction rate when the coal seam extraction meets the standard, which is greater than 29.82%, the corresponding coal seam gas pre extraction rate can be calculated under different spacing conditions and at different extraction times. The results are shown in Table 4 below.

Table 4. Relationship between gas pre extraction rate and time for different borehole spacing

Extraction time / days	Pre extraction rate (%) for different drilling spacing (m)					
	2m	3m	4m	5m	6m	7m
40	28.50	24.74	21.76	19.33	17.10	15.34
50	**31.87**	27.93	24.64	21.96	19.56	17.61
60	**34.42**	**30.41**	26.90	24.05	21.55	19.46
80	**37.80**	**33.84**	**30.09**	27.03	24.48	22.23
100	**39.73**	**35.93**	**32.06**	28.91	26.40	24.08
120	**40.83**	**37.19**	**33.28**	**30.10**	27.67	25.33
150	**41.67**	**38.22**	**34.29**	**31.11**	28.80	26.47
190	**42.10**	**38.80**	**34.89**	**31.72**	29.53	27.23
230	**42.24**	**39.02**	**35.11**	**31.97**	**29.85**	27.57
360	**42.30**	**39.14**	**35.25**	**32.12**	**30.07**	27.83
Notes	29.82% in the table represents the target pre extraction rate, and ranges below 29.82% are invalid values.					

As mentioned above, the gas pre extraction rate of the working face must reach the target value of 29.82% in order to meet the extraction standard. According to Table 4, it can be seen that:

(1) The pre extraction period is 50 days, and a pre extraction rate of 31.87% can be achieved when the spacing between boreholes is 2m. The spacing between other boreholes has not yet reached the standard. Therefore, the reasonable pre extraction time for the working face is determined to be 50 days, the spacing between boreholes is 2m, and the extraction radius is 1m.

(2) The pre extraction period is 60 days, and the pre extraction rate can reach 34.42% when the drilling spacing is 2 meters. The pre extraction rate can reach 30.41% when the drilling spacing is 3 meters. All other drilling spacings have not yet reached the standard. After 60 days of pre extraction period, the spacing between 2m and 3m boreholes can meet the standard for pre extraction, which means that the target pre extraction rate is achieved. Based on the comprehensive comparison of engineering quantity and pre extraction time, the reasonable pre extraction time for the working face is determined to be 60 days, the spacing between boreholes is 3m, and the extraction radius is 1.5m.

(3) The pre extraction period is 80 days, and the pre extraction rate can reach 37.80% when the drilling spacing is 2 meters. The pre extraction rate can reach 33.84% when the drilling spacing is 3 meters, and 30.09% when the drilling spacing is 4 meters. All other drilling spacing has not yet reached the standard for pre extraction. After a pre extraction period of 80 days, the spacing between 2m, 3m, and 4m boreholes can all meet the target pre extraction rate requirements. Based on a comprehensive comparison of engineering quantity and pre extraction time, the reasonable pre extraction time for the working face is determined to be 80 days, the spacing between boreholes is 4m, and the extraction radius is 2m.

(4) The pre extraction period is 120 days, and the pre extraction rate can reach 40.83% when the drilling spacing is 2m. The pre extraction rate can reach 37.19% when the drilling spacing is 3m, 33.28% when the drilling spacing is 4m, and 30.10% when the drilling spacing is 5m. The pre extraction rate has not yet reached the standard when the drilling spacing is 6m or 7m. After a pre extraction period of 120 days, the spacing between 2m, 3m, 4m, and 5m boreholes can all meet the target pre extraction rate requirements. Based on a comprehensive comparison of engineering quantity and pre extraction time, the reasonable pre extraction time for the working face is determined to be 120 days, the spacing between boreholes is 5m, and the extraction radius is 2.5m.

(5) The pre extraction period is 230 days. A pre extraction rate of 42.24% can be achieved when the drilling spacing is 2m, 39.02% can be achieved when the drilling spacing is 3m, 35.11% can be achieved when the drilling spacing is 4m, 31.97% can be achieved when the drilling spacing is 5m, 29.85% can be achieved when the drilling spacing is 6m, and the pre extraction rate has not yet reached the standard when the drilling spacing is 7m. After a pre extraction period of 230 days, the spacing between 2m, 3m, 4m, 5m, and 6m boreholes can all meet the target pre extraction rate requirements. Based on a comprehensive comparison of engineering quantity and pre extraction time, the reasonable pre extraction time for the working face is determined to be 230 days, the spacing between boreholes is 6m, and the extraction radius is 3m.

Due to the fact that drilling with a spacing of 7m can never meet the standard for extraction, it is not recommended to use a drilling spacing of 7m as a reasonable drilling spacing based on comprehensive considerations of engineering quantity and pre extraction time. According to the above analysis, the reasonable and effective extraction radius for a 50 day pre extraction of the mining face is 1m, the reasonable and effective extraction radius for a 60 day pre extraction is 1.5m, the reasonable and effective extraction radius for an 80 day pre extraction is 2m, the reasonable and effective extraction radius for a 120 day pre extraction is 2.5m, and the reasonable and effective extraction radius for a 230 day pre extraction is 3m.

5. Conclusion

In order to improve the utilization rate of coalbed methane in the mine and solve the problem of gas control, through on-site inspection and analysis research, it has been determined that the effective extraction radius of directional long boreholes in the No. 2 coal seam working face of a certain coal mine under different pre extraction times is: the reasonable effective extraction radius for pre extraction of 50 days is 1m; the reasonable and effective pumping radius for pre pumping for 60 days is 1.5m; the reasonable and effective pumping radius for pre pumping for 80 days is 2m; the reasonable and effective pumping radius for pre pumping for 120 days is 2.5m; the reasonable and effective extraction radius for 230 days of pre extraction is 3m. This provides a scientific basis for the rational design of directional long boreholes for coalbed methane extraction.

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