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Risk Analysis of Coal and Gas Outburst of Single Coal Seam in China: A Case Study

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Abstract

Determination of coal and gas outburst proneness in a coal seam is an important fundamental task for coal mine safety production. Based on the engineering geological conditions of a single coal seam in the Beiliu Area of Xi'an Coal Mine, Jilin Province, the coal and gas outburst risk of the Danyi Coal Seam was comprehensively assessed by observing and testing indicators, such as coal damage type, initial velocity of gas diffusion (Δp), coal hardness coefficient (f), virgin relative gas pressure (P), and coal seam gas content (W). The results show that the coal damage type is Class II, the maximum initial velocity of gas diffusion is 9.2 mmHg, the minimum coal hardness coefficient is 0.60, the maximum relative gas pressure is 0.14 MPa, the maximum gas content is 2.92 m^3/t, and the average gas content is 1.85 m^3/t. None of the individual outburst risk indicators reached the critical values, and no gas dynamic phenomena such as blowout or drill pipe jamming occurred within the assessment zone. Accordingly, it was determined that the coal seam has no coal and gas outburst risk within the area at a burial depth of less than 806.2 m (elevation −496.2 m). The research results can provide a reference for outburst risk determination of single coal seams under similar geological conditions.

Keywords

Coal and Gas Outburst, Single Coal Seam, Outburst Risk, Gas Pressure, Gas Content, Xi'An Coalmine, Jilin Province

1. Introduction

Coal and gas outburst is one of the major hazards in gas mines, often resulting in mass casualties and severely restricting the coal mine safe and efficient production. China is the country with the most severe coal and gas outburst disasters in the world (Wang et al., 2022). The combined-action hypothesis, which involves multiple factors such as *in-situ* stress, gas, and the strength of coal and rock mass, dominates the understanding of the mechanism of coal and gas outburst occurrence (Fan et al., 2026; Li & Lin, 2010). Numerous scholars have attempted to explain the mechanism of coal and gas outburst from an energy perspective (An et al., 2019; Ma et al., 2020; Sobczyk, 2014; Wang & Cheng, 2023; Hu et al., 2008); on the basis of the combined-action hypothesis, Chinese scholars have developed new views and theories, including the rheological hypothesis, the spherical shell instability theory, and the mechanical action hypothesis (Zhang et al., 2023). Outburst prediction based on gas indicators exhibits a one-to-one correspondence, but this correspondence varied among different coal samples, making it difficult to establish a unified critical value for coal seams with different degrees of metamorphism (Cheng & Zhou, 2021). To this end, many researchers have conducted extensive simulation experiments to better understand the mechanism of coal and gas outburst (Xu et al., 2006; Yuan et al., 2020; Zhang et al., 2022).

Determination of coal and gas outburst proneness in coal seams is a fundamental task for coal mine's newly building, reconstructing and expanding. In recent years, with the increase in mining depth and mining intensity, coal and gas outburst has occurred in some seams that never experienced outburst during shallow mining, and some low-gas mines have also experienced coal and gas outburst (Yuan et al., 2023). Therefore, in order to take preventive measures, avoid blindness in gas prevention and control, and achieve effective, reliable, and foreseeable outcomes, it is essential to measure basic gas parameters of a single coal seam and, on this basis, analyze the coal and gas outburst risk.

2. Mine Engineering Geological Conditions

2.1. Regional Location

The base map is sourced from the Standard Map Service of the Ministry of Natural Resources of China (http://bzdt.ch.mnr.gov.cn/browse.html?picId=%224o28b0625501ad13015501ad2bfc0288%22), Approval No. GS(2019)1673. The map has been modified only for visualization purposes (coloring and annotation).

Figure 1. Schematic diagram showing the location of the mining area.

Xi'an Coal Mine, Beiliu Area is located within Liaoyuan City, Jilin Province, at the northwestern end of the Liaoyuan Coalfield, extending 6.31 km from east to west and 1.66 km from north to south. The location of the mining area is shown in Figure 1.

2.2. Rock Strata and Geological Structure

The Beiliu Area is located within the Tianshan-Xing'an Geosynclinal Fold System, the Jihei Fold System (Grade I), the Jilin Eugeosynclinal Fold Belt (Grade II), and the Shiling Uplift (Grade III) in the northwestern part of the Liaoyuan Coalfield.

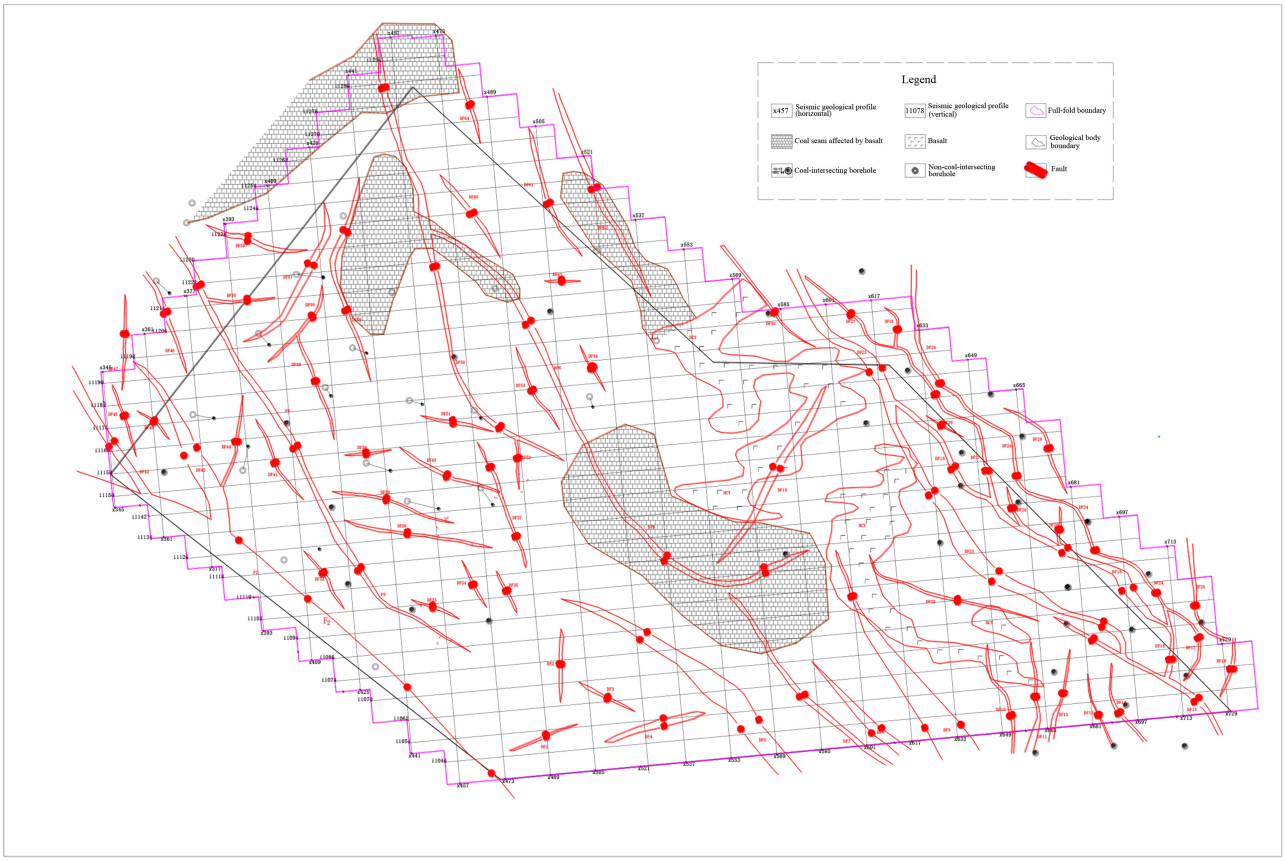


Figure 2. Structural outline of the mine.

The Beiliu Area is an asymmetric syncline opening to the northwest. The axis of the syncline trends northwest and plunges to the northwest. In this section, the entire southwestern limb in the southeastern part and most of the southwestern limb in the northwestern part are missing, leaving only the northeastern limb in the southeastern part of the syncline and most of the syncline at the northwestern end. Most of the rock strata dip at 297˚ with a dip angle of 10˚ - 25˚, forming the main structural framework of the Beiliu area. Additionally, ten strike or oblique faults have developed in this syncline. Most of the faults trend northwest, with a few trending northeast and nearly east-west. Based on the cross-cutting relationships among the faults, the earliest formed faults are the northwest- and nearly east-west-trending faults (F_2, F_4, F_9, F_{10}), followed by the northwest-trending faults (F_5, F_6, F_8), while the latest formed is the northeast-trending fault (F_1). The faults were generated after the Late Jurassic and before the Tertiary. The structural outline of the coal mine is shown in Figure 2.

The main faults characteristics are shown in Table 1.

Table 1. Summary of faults in the Beiliu Area.

Fault No.	Location	Extension length (m)	Type	Fault Attitude			Throw (m)	Controlled Degree
				Strike	Dip	Dip Angle (˚)		
F_1	Eastern part of the minefield	>3700	Strike-slip	50	320		370	Inferred
F_2	Southern part of the minefield	>5200	Normal	108	18	55 - 74	>650	Inferred
F_3	Southwestern part of the minefield		Reverse	110	20	70	30	Controlled
F_4	Central part of the minefield	1300	Normal	140	230	55 - 65	40 - 50	Inferred
F_5	Central part of the minefield	750	Normal	150	240	70	<60	Inferred
F_6	Central part of the minefield	2200	Reverse	0 - 150	240 - 270	55 - 60	70 - 110	Controlled
F_7	Northwest of the minefield	>300	Normal	Northwest	Southwest		15	Inferred
F_8	Central part of the minefield	>2600	Normal	0 - 135	225 - 270	55 - 70	46 - 66	Inferred
F_9	Central part of the minefield	>450	Normal	280	190	67	<40	Controlled
F_{10}	Northeastern part of the minefield	>1500	Normal	300 - 325	30 - 55	50 - 60	60 - 70	Controlled
F_{11}	Western side of the minefield		Normal		Northeast	30 - 45		Inferred

2.3. Coal Seam and Its Roof and Floor

Danyi Coal Seam is the single minable coal seam in the Beiliu Area, which occurs at the bottom of the mudstone sub-member of the lower coal-bearing section (J_3^{2-1}) of the Liaoyuan coal-bearing group (J_3^2). Danyi Coal Seam is mostly minable in the mining area. The coal seam is relatively well-developed and its strata horizon is stable. The controlled strike length is about 1.5 km, and the controlled dip extension is about 2.4 km. The dip of the coal seam is 297˚, the dip angle is 10˚ - 25˚. The coal seam thickness is 0.70 - 6.06 m, with an average thickness of 2.68 m. The variation coefficient of the coal seam thickness is 63%, and the occurrence elevation is from −130 m to −1000 m. The coal seam structure is simple, generally containing 1 - 3 layers of parting. The thickness of the parting is generally about 0.2 m, with a maximum thickness of 0.48 m. The parting is mostly mudstone and carbonaceous mudstone. The coal seam is relatively thin and the thickness variation is not large. From the limb to the axis of the syncline, the coal seam thickness gradually increases, and the number and thickness of the parting in the coal seam also tend to increase.

The roof of the coal seam is a black mudstone marker layer, with a thickness of 2.70 - 75.00 m and an average thickness of 35.00 m. The floor of the coal seam is thin-layer mudstone, carbonaceous mudstone, tuffaceous sandstone, and tuff, with a thickness of 0 - 11.20 m.

2.4. Gas Occurrence Conditions

The absolute gas emission of the mine is 13.53 m^3/min, and the relative gas emission is 3.79 m^3/t. The maximum absolute gas emission of the coal-mining face is 7.18 m^3/min, and the maximum absolute gas emission of the tunneling face is 1.45 m^3/min. It is a high-gas mine. No gas dynamic phenomena such as hole-spraying and drill-jamming have occurred during the daily mining process.

3. Implementation Plan

In accordance with the relevant provisions of China's "Specifications for Identification of Coal Mine Gas Grade" (GB 40880-2021), "Detailed Rules for Prevention and Control of Coal and Gas Outbursts," and "Measures for Identification of Coal Mine Gas Grade," for coal seams where no gas dynamic phenomena have occurred, the identification of outburst risk shall be carried out using the actually measured outburst risk indicators.

Since no coal and gas dynamic phenomena have occurred in the Danyi Coal Seam of the Xi'an Coal Mine, the determination and analysis are carried out using the initial velocity of gas emission (Δp), the firmness coefficient of coal (f), the original gas pressure (relative) in the coal seam (P), and the coal destruction type. Combined with the actual underground measurement of the original gas content of the coal seam (W), the coal and gas outburst risk of the Danyi Coal Seam in the mine was tested and analyzed. The critical values for each indicator are based on the Chinese standard "Specification for Identification of Coal Mine Gas Grade" (GB 40880-2021). Among them, gas content serves as an auxiliary indicator, which is determined by the assessment agency based on experience combined with specific regional conditions.

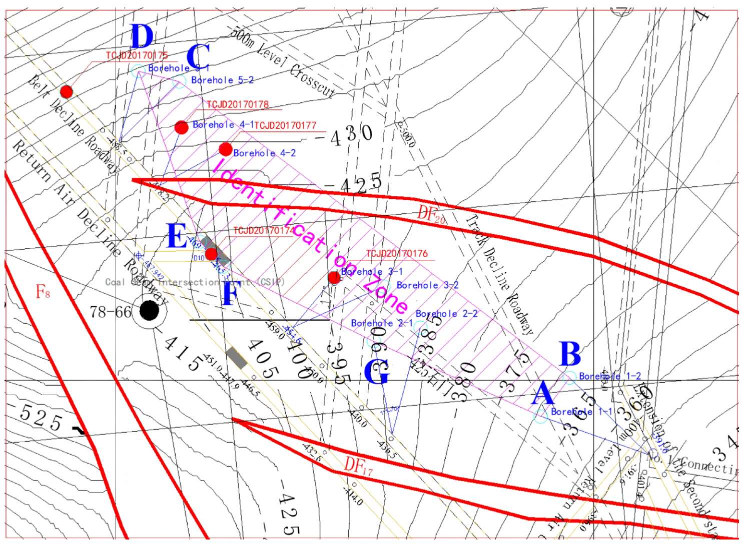


Figure 3. Identification implementation plan.

The Beiliu Area, only the area below the −400 m station contains original coal bodies unaffected by mining. In this area, the −400 m station to the −550 m level is currently in the stage of development and extension, with only two rock roadways in the coal seam floor—the belt conveyor dip and the second-stage dark return air shaft extension—under construction. Therefore, the zone for carrying out coal and gas outburst identification is limited. Based on the drilling capability of the mine's cross-layer pressure-measuring boreholes, the work can only be carried out within the area delineated by inflection points A to G. This area is irregular in shape, with a length of only 220 m and a width of only 50 m. The identification zone, pressure-measuring boreholes, and sampling point layout are shown in Figure 3.

4. Determination of Identification Indicators

4.1. Investigation of Coal Failure Type

Coal failure type refers to the category formed due to different degrees of destruction of the coal body structure under the action of tectonic stress, resulting in different physical and mechanical properties and characteristics of the coal. The more severe the coal failure, the greater the outburst risk. When determining the coal failure type, the following aspects are generally considered: coal luster, coal structure and structural characteristics, coal joint properties, coal joint surface properties, coal strength, and coal fracture properties. According to the "Regulations on Prevention and Control of Coal and Gas Outbursts," coal failure types are classified into Types I, II, III, IV, and V. The outburst risk of coal increases gradually from Type I to Type V. Generally, Types I and II belong to the non-outburst-prone type, Type III belongs to the outburst-prone type (tending to be dangerous), and Types IV and V belong to the outburst-prone type.

On-site observations were carried out on newly exposed coal seams at locations such as the Belt Decline Roadway (BDR) in the Danyi Coal Seam of the Beiliu Area. The observation points are arranged as shown in Figure 3, numbered TCJD20170174, TCJD20170175, TCJD20170176, TCJD20170177, and TCJD20170178. Coal samples at these points were mainly collected from the soft sub-layer within the observed coal seam, representing the portion of the entire seam most prone to outburst. Through methods such as visual inspection and hand manipulation, it was found that the Danyi Coal Seam exhibits a vitreous to greasy luster, belonging to the semi-bright to semi-dark type. In terms of structure and texture, the coal seam shows relatively obvious horizontal bedding and is basically layered in structure. Regarding joint properties, secondary joint surfaces are relatively developed and irregular. In terms of joint surface properties, the joint surfaces are slippery and can be easily broken apart by hands. As for fracture properties, the fractures are conchoidal and irregular. A comprehensive judgment indicates that the Danyi Coal Seam belongs to Type II failure type.

4.2. Initial Velocity of Gas Emission and Firmness Coefficient

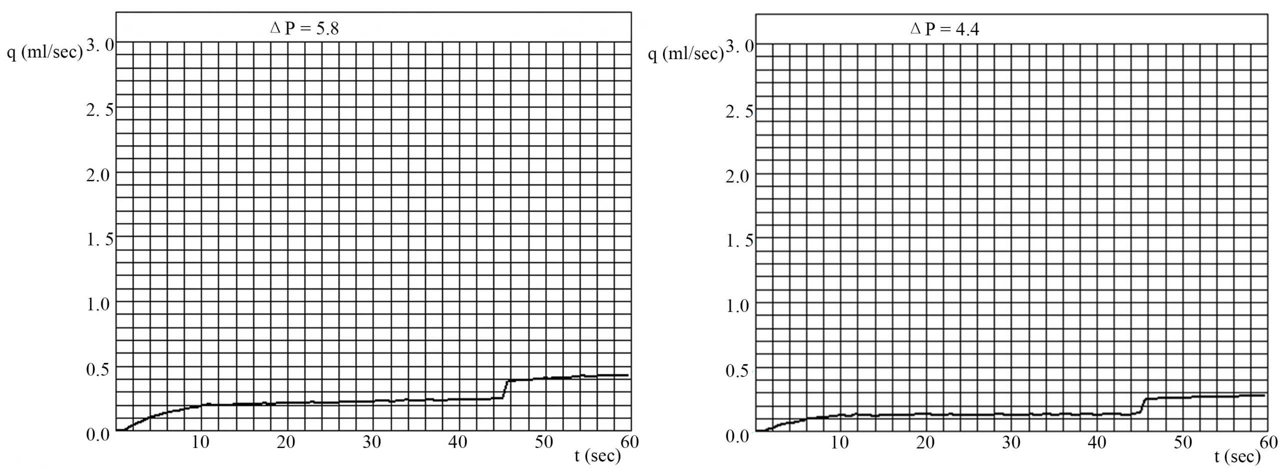
The initial velocity of gas emission (Δp) is one of the indicators for predicting the risk of coal and gas outburst. This indicator reflects the coal's ability to adsorb gas under atmospheric pressure and the speed of gas emission (the transition of gas from adsorbed state to free state) when the gas-bearing coal body is exposed. The initial velocity of gas emission can reflect the pore structure and microscopic degree of failure of the coal. The performance of coal in emitting gas is determined by the physical and mechanical properties of the coal. It is a single indicator reflecting the risk of outburst in a coal seam area. In the development process of coal and gas outburst, the movement and destructive force of gas largely depend on the desorption and emission capacity of gas when the gas-bearing coal body is destroyed. Under the same gas content conditions, the greater the initial velocity of gas emission of the coal, the more favorable it is for the occurrence and development of outbursts.

The firmness coefficient of coal (*f*) is a comprehensive indicator representing the ability of coal to resist external destructive forces. In essence, it reflects the amount of energy consumed per unit mass of coal when destroyed. The firmness coefficient of coal is mainly determined by the physical and mechanical properties of the coal. The greater the strength of the coal body, the higher the firmness coefficient, the greater the resistance encountered during coal and gas outburst, and the lower the possibility of outburst occurrence.

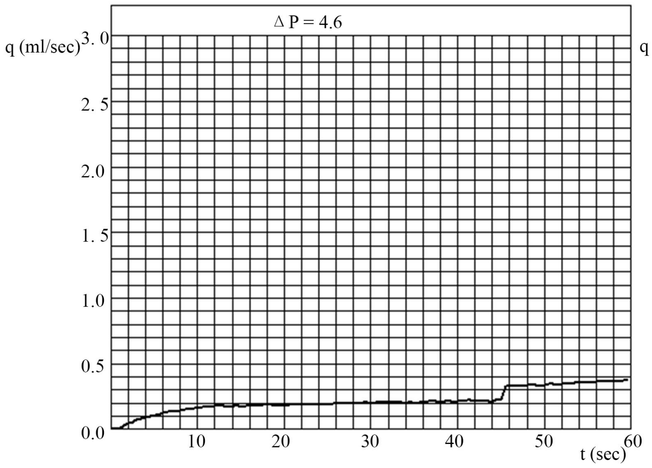
Coal samples of the Danyi Coal Seam were collected at five sampling points from exposed coal seams or through core drilling, and the sampling and tested results are detailed in Figure 4 and Table 2.

Table 2. Tested results of initial velocity of gas emission (Δp) and firmness coefficient (f).

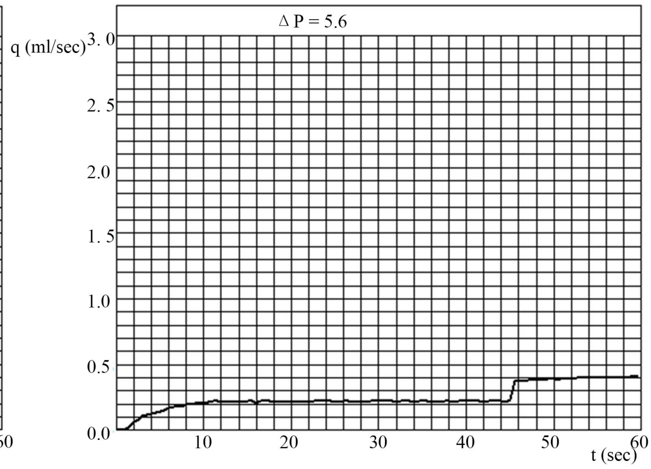
Coal Seam	Coal Sample No.	Sampling Location	Δp (mmHg)	f
Danyi Coal Seam	TCJD20170174	226 m at of Belt Decline Roadway	5.8	0.60
	TCJD20170175	310 m at of Belt Decline Roadway	4.4	0.86
	TCJD20170176	Borehole 3-1, 178 m at of Belt Decline Roadway	4.6	1.03
	TCJD20170177	Borehole 4-2, 260 m at of Belt Decline Roadway	5.6	1.33
	TCJD20170178	Borehole 4-1, 260 m at of Belt Decline Roadway	9.2	1.25



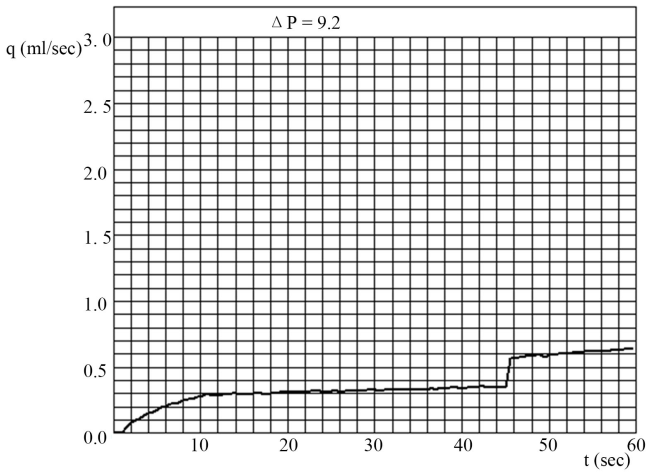
(a) TCJD20170174 (b) TCJD20170175



(c) TCJD20170176



(d) TCJD20170177



(e) TCJD20170178

Figure 4. Gas emission curve of Danyi coal seam coal samples.

4.3. Determination of Coal Seam Gas Pressure

Coal seam gas pressure is one of the main indicators for judging the risk of coal and gas outburst. Gas pressure is also an important indicator of the level of gas compression energy contained in the coal body, serves as the necessary driving force for the occurrence of coal and gas outburst, and is a necessary condition for the occurrence of coal and gas outburst.

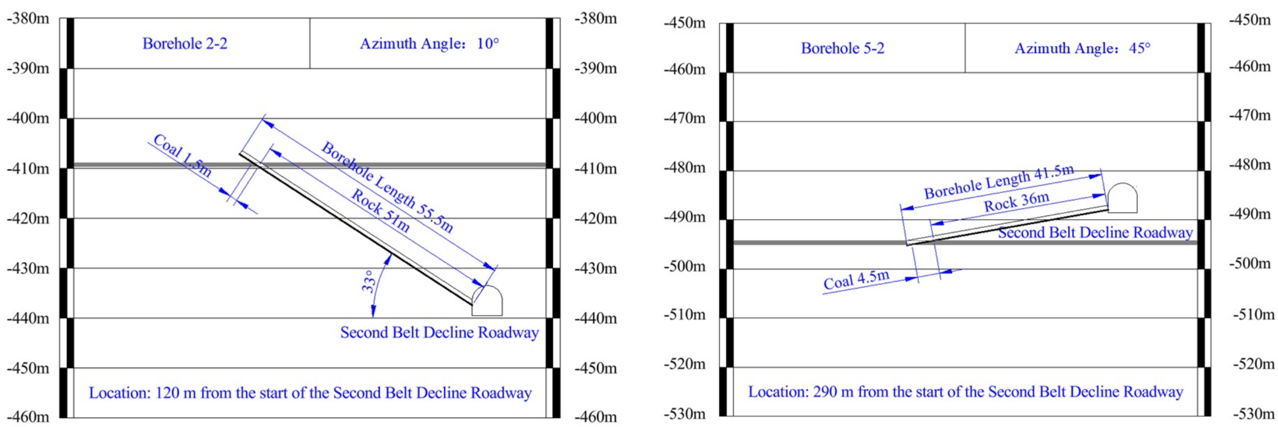
Based on the existing roadway layout and coal seam exposure conditions in the mine within the identification zone, and after comprehensive analysis of rock fracture development, coal seam exposure time, roadway cross-section size, and other factors, two rock roadways—the Extension of the Second-stage Blind Return Air Shaft (ESBRAS) and the Belt Decline Roadway (BDR)—were adopted to carry out a total of 5 measurement points (10 cross-layer boreholes) to determine the coal seam gas pressure, among which measurement point No. 5 is located at the deepest part of this identification zone. The starting point of upward boreholes is 1.5 m to 2.0 m from the roadway floor, while that of downward boreholes is about 0.5

m from the roadway floor. The completion parameters of the boreholes are listed in Table 3. The borehole diameter is 113 mm, and the cross-layer pressure-measuring boreholes penetrate the full thickness of the coal seam. During the construction of all boreholes, no gas dynamic phenomena such as bit pulling or blowout were encountered in the Danyi Coal Seam. The passive pressure measurement method was adopted for this identification to measure the gas pressure of the Danyi Coal Seam.

Table 3. Completion parameters of boreholes for gas outburst identification.

Borehole No.	Measurement Location	Borehole Parameters		CIP[a]			Rock Part (m)	Coal Part (m)	Whole Length (m)	Sealing Length (m)
		Azimuth	Inclination	SPE[b] (m)	CSFE[c] (m)	CSBD[e] (m)				
1-1	Intersection of ESBRAS and BDR	291	25	−390.1	−367.9	677.9	53.25	3.75	57	30
1-2		304	25	−390.1	−368.6	678.6	54	9	63	40
2-1	120 m, BDR	349	28	−437.5	−416.4	726.4	48	2.5	50.5	30
2-2		10	33	−437.5	−409.7	719.7	54	1.5	55.5	30
3-1	170 m, BDR	33	38	−452.6	−436.0	746.0	29.5	4.5	34	20
3-2		66	43	−452.6	−413.7	723.7	59.25	6.75	66	20
4-1	265 m, BDR	20	−15	−477.7	−485.7	795.7	32.5	4.5	37	20
4-2		45	−10	−477.7	−482.9	792.9	31	3.5	34.5	20
5-1	290 m, BDR	15	−15	−488.0	−496.2	806.2	32.5	4	36.5	20
5-2		45	−10	−488.0	−494.3	804.3	37	4.5	41.5	20

a. Coal Intersection Point; b. Starting Point Elevation; c. Coal Seam Floor Elevation; d. Coal Seam Burial Depth; e. Coal Seam Burial Depth.



(a) Cross-section of Upward Borehole (b) Cross-section of Downward Borehole

Figure 5. Typical borehole cross-section.

Cement slurry was used as the sealing material. The sealing length of cross-layer boreholes depends on the lithology of the coal seam roof (or floor) and the borehole length. The pressure measuring pipe is connected using 4-point seamless steel pipes with threads at both ends. At the bottom section of the borehole, within

0.5 m from the end, sieve holes are made to serve as the gas inlet channel. Each section of the pressure measuring steel pipe is 2 m in length. To ensure the airtightness, the pipe joints are wrapped with PTFE tape. The end of the pressure measuring tail pipe is wrapped with fine copper gauze to prevent coal chips and debris from entering and clogging the pipeline. The cross-section of the completed boreholes is shown in Figure 5.

The gas pressure observation results were recorded on a coal seam gas pressure measurement record sheet, and plotted on a coordinate graph with time (T/d) as the horizontal axis and gas pressure (P/MPa) as the vertical axis. If the pressure observation time meets the above principles and the pressure change is less than 0.015 MPa within 3 days, the pressure measurement work can be concluded, and the current pressure is the final gas pressure (relative pressure) of that pressure-measuring borehole. The general pressure observation period should be no less than 30 days.

Table 4. Summary of coal seam gas pressure determination results.

Borehole No.	Measurement Location	CSFE (m)	CSBD (m)	Coal Seam Gas Pressure (Relative) *P* (MPa)
1-1	Intersection of ESBRAS and BDR	−367.9	677.9	0
1-2		−368.6	678.6	0
2-1	120 m, BDR	−416.4	726.4	0
2-2		−409.7	719.7	0.140
3-1	170 m, BDR	−436.0	746.0	0
3-2		−413.7	723.7	0
4-1	265 m, BDR	−485.7	795.7	0
4-2		−482.9	792.9	0
5-1	290 m, BDR	−496.2	806.2	0.040
5-2		−494.3	804.3	0.105

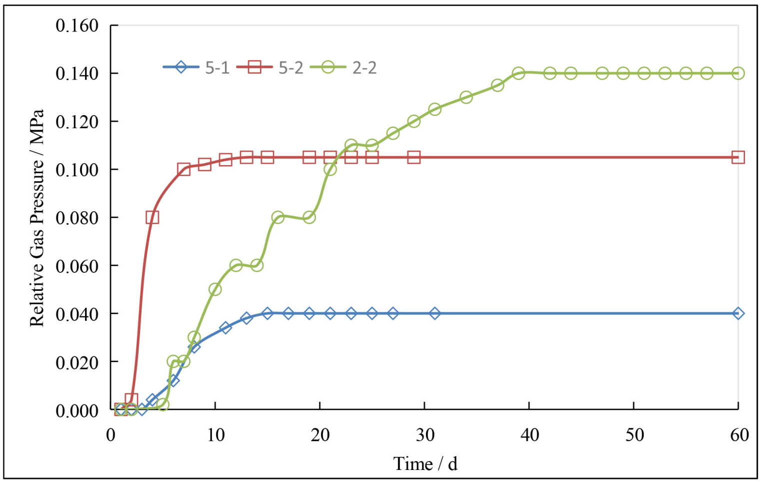


Figure 6. Gas pressure rise curve of pressure-reading boreholes in the Danyi coal seam.

Ultimately, the readings of pressure gauges at Borehole 1-1#, 1-2#, 2-1#, 3-1#, 3-2#, 4-1#, and 4-2# were 0 MPa; 5-1# was 0.040 MPa, 5-2# was 0.105 MPa, and 2-2# was 0.140 MPa, as shown in **Table 4**. The observation results were plotted, as shown in **Figure 6**.

4.4. Coal Seam Gas Content

For gas content determination, coal samples were taken using a fixed-point sampling device at a sampling depth of 25 m. The determination results of the coal seam gas content are shown in **Table 5**.

Table 5. Summary of gas content determination results.

Coal Seam	Coal Sample No.	Coal Gas Content (m^3/t)	Burial Depth (m)	Test Method	Evaluation
Danyi Coal Seam	−270 m Level Return Air Crosscut	2.92	580	Direct method	Reference
	230 m, E103 Working Face Headgate	1.95	710	Direct method	Adopted
	45 m, E104 Working Face Tailgate	1.33	547	Indirect method	Adopted
	170 m, E103 Working Face Tailgate	1.19	525	Indirect method	Adopted
	Average	1.85	590.5	/	/

It can be seen that the gas content of the Danyi Coal Seam ranges from 1.19 m^3/t to 2.92 m^3/t, with a maximum gas content of 2.92 m^3/t and an average gas content of 1.85 m^3/t. Gas is generated in and stored in the coal seam. The magnitude of gas content is also closely related to the burial depth of the coal seam: the deeper the burial depth, the less likely the gas is to escape, so more gas is stored in the coal seam, resulting in a higher gas content, and vice versa.

In **Table 5**, the gas content at the −270 m level return air crosscut significantly deviates from the overall gas distribution in the area, indicating that this point is influenced by local geological structures and should only be used as a reference for analyzing gas distribution patterns. The analysis of gas distribution patterns was conducted using the other three measurement points.

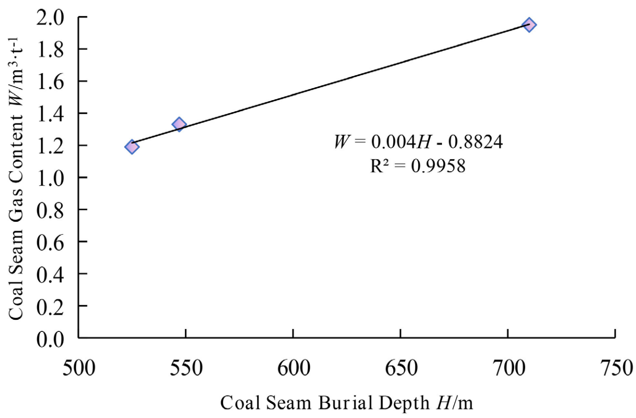


Figure 7. Relationship between gas content and burial depth.

Using the *Adopted* data of the Single Coal Seam gas content in **Table 5**, the relationship curve between gas content and burial depth for the single coal seam is shown in **Figure 7**.

As can be seen from **Figure 7**, the gas content of the Danyi Coal Seam in the Beiliu Area of Xi'an Coal Mine increases with the increase of coal seam burial depth. There is a good linear statistical relationship between the gas content and burial depth of this coal seam (correlation coefficient $R^2 = 0.9958$), as shown in Equation (1).

$$W = 0.004H - 0.8824 \quad (1)$$

where:

W—coal seam gas content, m^3/t;

H—coal seam burial depth, m.

Gas content gradient refers to the average increase in gas content for every 100 m increase in coal seam burial depth. From Equation (1), it can be seen that the gas content growth gradient of the Danyi Coal Seam is 0.4 (m^3/t)/(100 m), that is, for every 100 m increase in depth, the coal seam gas content increases by 0.4 m^3/t.

5. Outburst Risk Analysis

During the construction of the test boreholes, no gas abnormal phenomena such as blowout or bit pulling were observed. The summary of coal and gas outburst identification indicators is shown in **Table 6**.

Table 6. Determination results of identification indicators.

Coal Seam	Identification Indicators	Coal Destruction Type	Initial Gas Emission Velocity Δp (mmHg)	Coal Firmness Coefficient f	Relative Gas Pressure P (MPa)
Danyi Coal Seam	Critical Value	III, IV, V	≥10	≤0.5	≥0.74
	Measured Value	Type II	9.2	0.60	0.14
	Whether the critical value is reached	Not Reached	Not Reached	Not Reached	Not Reached

For the single coal seam (Danyi Coal Seam) in the Beiliu Area, Xi'an Coal Mine, it is located within the same gas-geological unit. The gas pressure measurement points include no fewer than 3 points along the strike direction and no fewer than 3 points along the dip direction, with measurement points also arranged at the lowest elevation and maximum burial depth within the identified area. This arrangement complies with the requirements of the Chinese standard "Specification for Identification of Coal Mine Gas Grade" (GB 40880-2021). Therefore, the test results are representative of the entire identified area. All the four individual indicators of the coal seam outburst risk measured within the identification zone did not reach the critical values for determining single coal seam outburst risk indicators stipulated in the outburst prevention regulations. Moreover, no coal and gas outburst dynamic phenomena have ever occurred in the mining activities in the Beiliu Area. Consequently, it is hereby determined that, within the delineated area of the Danyi Coal Seam in Beiliu Area, the region at a burial depth of 806.2 m (elevation −496.2 m) and shallower exhibits no proneness to coal and gas outburst.

6. Conclusions

1) In the Danyi Coal Seam of the Beiliu Area, the maximum coal failure type is Type II, the maximum initial velocity of gas emission is 9.2 mmHg, the minimum firmness coefficient of coal is 0.6, and the maximum original gas pressure (relative) in the coal seam is 0.14 MPa.

2) The average gas content of the Danyi Coal Seam in the Beiliu Area is 1.85 m^3/t, and the maximum gas content is 2.92 m^3/t. The gas content shows an increasing trend with the increase of coal seam burial depth, and the gas content growth gradient of the Danyi Coal Seam is 0.4 (m^3/t)/100 m.

3) In Beiliu Area of Xi'an Coal Mine, within the identification zone, the area with a burial depth of less than 806.2 m (elevation −496.2 m) has no risk of coal and gas outburst.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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