



Study on Layered Measurement Analysis of Comprehensive Gas Extraction by Cross-measure Boreholes in Coal Seam Groups

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Abstract. Combined gas extraction using cross-measure boreholes in coal seam groups is a key technology for gas control in highly gassy mines. However, it is difficult to separately measure the gas contribution of each coal seam under mixed extraction conditions. This situation seriously restricts the accurate evaluation of extraction standards and the calculation of residual gas content. To solve this problem, based on the law of conservation of mass for carbon isotopes of mixed-source gases, a layered measurement model for comprehensive gas extraction by cross-measure boreholes in coal seam groups was constructed. Taking No.9 and No.10 coal seams in Shanjiaoshu Coal Mine, Guizhou Province as the research object, on-site sampling and laboratory tests were carried out to measure the volume fraction of gas components and methane carbon isotope values of each coal seam, and the gas mixing ratio of each coal seam in combined extraction was calculated. The results show that there are significant differences in methane carbon isotope values between No.9, No.10 coal seams and mixed gas, which can be used as the basis for layered measurement; the average value of three measuring points shows that the gas proportion of No.9 coal seam is 56.24%, and that of No.10 coal seam is 43.76%. The research realizes accurate layered measurement of gas extracted from coal seam groups, providing scientific and technical support for inspecting gas extraction effects, evaluating compliance standards, and preventing gas-related disasters.

Keywords: Coal Seam Groups; Cross-measure Boreholes; Gas Extraction; Carbon Isotope.

1 Introduction

Gas pre-drainage by boreholes is the mainstream technical means for gas disaster prevention and coalbed methane development in coal mines [1-2]. According to the Provisional Regulations on Standardized Gas Extraction in Coal Mines, effect evaluation must be carried out after coal seam pre-drainage; failure to meet the standards before

mining and excavation operations can easily trigger major or extremely serious accidents such as gas overruns and outbursts [3-4]. Most mines in China adopt a coal seam group mining mode; before rock-cross-cut coal uncovering and coal roadway driving, cross-measure boreholes are generally constructed in roof and floor rock roadways to achieve joint gas extraction from multiple coal seams [5-7]. This method improves borehole utilization and reduces governance costs, thereby serving as a key technology for ensuring safe and efficient mine production. However, since coal seam groups produce mixed gas during joint extraction, existing measurement methods and devices can only measure the total extraction volume and cannot separate the actual gas contribution of each coal seam. This results in the absence of residual gas content calculations for single coal seams and creates a lack of scientific basis for effect inspection, thereby introducing significant safety hazards for mining and excavation operations.

Research on oil and gas reservoir sources based on carbon isotopes has achieved many results in the oil and gas industry [8-9]. Liang used natural gas isotope principles to calculate and determine the amount of mixed gas and applied it in the Hexiwu structural belt of the Langgu sag [10]. Li and Yuan used a combination of natural gas component carbon isotopes and chromatographic hydrocarbon fingerprinting technology to quantitatively obtain the mixing ratios of various organic-origin natural gases [11-12]. Meng and Meng established a linear relationship between the methane carbon isotope of mixed gas and the mixing ratio to classify the precise proportions of coal-derived gas and oil-type gas in mixed-source gas reservoirs [13-14]. Building upon the research results of Dai Jinxing et al. [15], Yin conducted a study that compared the differences in stable isotopes between gas in coal mine goafs and desorbed gas in target strata, combined with the gas concentration from goaf emissions, the coal seam itself, and adjacent layers to determine the source of gas in the goaf [16]. Gao determined the sources and proportions of multi-source gas in mining faces based on the differences in carbon and hydrogen isotopes between single coal seam gas and multi-seam mixed gas [17]. The studies of the above scholars have laid the foundation for applying carbon isotopes to gas sources in joint gas extraction from coal seam groups.

This paper, based on the law of mass conservation of the chemical composition of mixed-source gases, establishes a calculation model for mixed-source gas proportions, takes the No.9 and No.10 coal seam groups in Shanjiaoshu Coal Mine, Guizhou as the research object, and calculates the gas mixing ratio of each coal seam in the joint extraction of coal seam groups by measuring the volume fraction of gas components and their carbon isotopes in each coal seam. The research results can thereby establish a theoretical framework for evaluating the compliance of joint gas extraction across multiple coal seams.

2 Experimental Method

2.1 Model Establishment

Stable isotope geochemistry mainly studies the abundance and variation laws of stable isotopes in nature [18-19]. Carbon has two stable isotopes, ^{12}C and ^{13}C . The abundance

of ^{12}C in internationally recognized PDB standard samples is 98.892%, and the abundance of ^{13}C is 1.108%. The carbon isotope value $\delta^{13}\text{C}$ can be defined by the following formula.

$$\delta^{13}\text{C} = \left(\frac{\left(\frac{^{13}\text{C}}{^{12}\text{C}} \right)_{\text{Sam}}}{\left(\frac{^{13}\text{C}}{^{12}\text{C}} \right)_{\text{Sta}}} - 1 \right) \times 1000 \quad (1)$$

Where: $(^{13}\text{C}/^{12}\text{C})_{\text{Sam}}$ and $(^{13}\text{C}/^{12}\text{C})_{\text{Sta}}$ represent the $^{13}\text{C}/^{12}\text{C}$ abundance ratio of the test and standard sample.

The gas component containing carbon is mainly methane (CH_4). According to the principle of chemical composition mass conservation of mixed-source gas carbon isotopes, assuming the mixing of No.9 and No.10 coal seam gas in Shanjiaoshu Mine, the methane carbon isotope value of the mixed gas can be derived from the definition of carbon isotope values:

$$\delta^{13}\text{C}(\text{CH}_4)_{\text{mix}} = \frac{v(\text{CH}_4)_9 \delta^{13}\text{C}(\text{CH}_4)_9 + v(\text{CH}_4)_{10} \delta^{13}\text{C}(\text{CH}_4)_{10}}{v(\text{CH}_4)_9 + v(\text{CH}_4)_{10}} \quad (2)$$

Where: $\delta^{13}\text{C}(\text{CH}_4)_9$ and $\delta^{13}\text{C}(\text{CH}_4)_{10}$ represent the CH_4 carbon isotope value of No.9 and No.10 coal seam gas, $v(\text{CH}_4)_9$ and $v(\text{CH}_4)_{10}$ represent the CH_4 volume of No.9 and No.10 coal seam gas.

The CH_4 volume of the gas can be expressed as:

$$\begin{cases} v(\text{CH}_4)_9 = V_9 \cdot w(\text{CH}_4)_9 \\ v(\text{CH}_4)_{10} = V_{10} \cdot w(\text{CH}_4)_{10} \end{cases} \quad (3)$$

Where: V_9 and V_{10} represent the gas volume of No.9 and No.10 coal seam, $w(\text{CH}_4)_9$ and $w(\text{CH}_4)_{10}$ represent the CH_4 component content of No.9 and No.10 coal seam gas.

Assuming no chemical reaction between gas molecules occurs, the volume after the two groups of gas is mixed is the sum $V_9 + V_{10}$, and the proportions of the two groups of gas in the mixed volume are $a = V_9 / (V_9 + V_{10})$ and $b = V_{10} / (V_9 + V_{10})$ respectively. Substituting them into formula (2) to formula (3), the layered measurement model for comprehensive extraction by cross-measure boreholes in coal seam groups is established:

$$\begin{cases} a + b = 1 \\ \delta^{13}\text{C}(\text{CH}_4)_{\text{mix}} = \frac{aw(\text{CH}_4)_9 \delta^{13}\text{C}(\text{CH}_4)_9 + bw(\text{CH}_4)_{10} \delta^{13}\text{C}(\text{CH}_4)_{10}}{aw(\text{CH}_4)_9 + bw(\text{CH}_4)_{10}} \end{cases} \quad (4)$$

In the field test, by testing the CH_4 component content and carbon isotope values of the No.9 and No.10 coal seam gases and the mixed gas in Shanjiaoshu Mine, the proportions of the two groups of gas in the mixed volume can be solved separately.

2.2 Experimental Scheme

Shanjiaoshu Coal Mine treats the non-mineable No. 9 coal seam and the primary No. 10 coal seam as a single entity for joint gas extraction via cross-measure boreholes. To obtain accurate gas contribution data, three groups of measuring points were established in the 211014-return air roadway. Each group included three types of boreholes:

- Boreholes 1-1, 2-1, 3-1: Upward cross-measure boreholes penetrating the No. 9 coal seam for individual gas sampling.
- Boreholes 1-2, 2-2, 3-2: Upward cross-measure boreholes penetrating both the No. 9 and No. 10 coal seams for mixed gas sampling.
- Boreholes 1-3, 2-3, 3-3: Pre-constructed in-seam boreholes of the No. 10 coal seam for individual gas sampling.

3 Experimental Instruments

3.1 Sampling Equipment

Gas extraction samples were prepared using a gas collection device and gas sampling bags, as shown in Fig. 1, at the flow measurement point of the extraction borehole orifice. Coal seam gas samples were collected using a CFZ22(A) automatic negative pressure gas sampler and 100 mL aluminum foil sampling bags.



Fig.1. Gas sampling instruments: (a) Gas sampler; (b) Sampling bags.

3.2 Test Instruments

Gas component analysis was completed by an 8890-gas chromatograph (equipped with a large valve box) produced by Agilent. The analysis process was strictly executed in accordance with the methods in GB/T 13610-2020 "Analysis of natural gas composition - Gas chromatography".

Gas carbon isotope analysis was completed by a 6890N gas chromatograph produced by Agilent and an Isoprime100 isotope ratio mass spectrometer produced by Elementar. The analysis process was strictly executed in accordance with SY/T 5238-2019 "Analytical method for carbon and oxygen isotopes of organic matter and carbonate rocks" [20].

4 Experimental Results and Analysis

4.1 Test Results of Gas Components and Carbon Isotopes

All gas samples sequentially completed the quantitative analysis of gas components and the tests for methane, carbon dioxide, and ethane carbon isotope ratios. After excluding abnormal data caused by potential issues such as on-site air leakage or air infiltration, the molar percentage contents of components and carbon isotope test results for each gas sample were obtained, as shown in Table 1.

Table 1. Revised gas components and test results of carbon isotopes

Sample Number	Gas Molar Percentage Content/%					$\delta^{13}\text{C}/\text{‰}$			Belonging Coal Seam
	CH ₄	C ₂ H ₆	CO ₂	O ₂	N ₂	CH ₄	CO ₂	C ₂ H ₆	
1-1	94.67	1.40	0.78	0	0.82	-47.47	16.46	-26.53	No. 9
1-2	44.91	0.33	3.01	0	46.70	-46.78	-5.63	-27.25	No. 9 and No. 10
1-3	72.19	0.12	4.08	0	19.58	-44.9	-7.63	-25.04	No. 10
						-44.93	-6.59	-25.75	
2-1	86.39	0.09	4.24	0	4.99	-46.11	-3.1	-26.61	No. 9
2-2	94.03	1.08	1.11	0	1.32	-46.28	14.82	-26.91	No. 9 and No. 10
2-3	45.99	1.40	1.20	0	47.70	-44.97	7.4	-26.73	No. 10
3-1	95.76	0.49	1.47	0	1.49	-47.05	22.06	-26.94	No. 9
						-46.87	22.64	-26.48	
3-2	96.73	1.41	1.34	0	0.22	-46.21	24.42	-26.43	No. 9 and No. 10
3-3	51.72	0.03	9.70	0	36.38	-52.54	-11.05	-27.28	No. 10

From the test results in Table 1, the carbon isotope test results exhibit clear differentiation characteristics. There are significant differences in methane carbon isotope values between different coal seams. The methane carbon isotopes of the No. 9 coal seam are distributed between -47.47‰ and -46.87‰, with values generally lighter and concentrated in the distribution interval. The methane carbon isotopes of the No. 10 coal seam are distributed between -52.54‰ and -44.90‰, with relatively greater data dispersion. The methane carbon isotopes of the mixed gas stably fall within the range of -46.78‰ to -46.21‰, lying between the values of the two single coal seams, a fact that entirely conforms to the linear mixing law of binary mixed-source gas isotopes and provides a reliable data basis for layered measurement calculations.

4.2 Analysis of Carbon Isotope Differences in Gas Components

Typicality analysis was performed on the test data in Table 1, removing data with obvious anomalies; the comparison of processed methane carbon isotope values is shown in Figure 2.

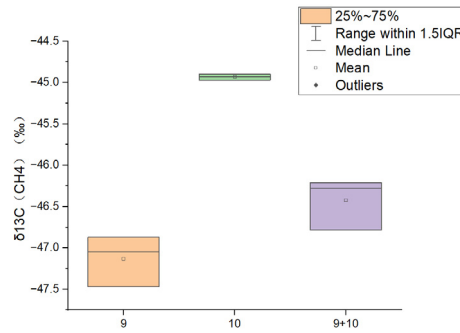


Fig. 2. Comparison of methane carbon isotope values of gas samples

From Figure 2, there are significant differences in the CH_4 carbon isotope values between each coal seam and joint extraction. The methane carbon isotope values of the No. 9 coal seam gas samples are between -47.47‰ and -46.87‰ , with a wider distribution range and stronger discreteness, but they exhibit stable and homogeneous isotope composition characteristics; this is closely related to the No. 9 coal seam being a non-mineable thin coal seam with a high degree of coalification, sufficient thermal evolution, and a long-term stable gas generation and occurrence environment. The methane carbon isotope values of the No. 10 coal seam gas samples are between -44.97‰ and -44.9‰ , with a narrow distribution interval and high data concentration, and are generally heavier than those of the No. 9 coal seam; this characteristic reveals that as the mine's primary mining seam, the No. 10 coal seam has been subjected to the combined effects of long-term mining disturbances, dynamic changes in ground stress, and spatial differences in surrounding rock permeability, making the processes of gas migration, desorption, and emission more complex, which in turn leads to certain fluctuations in isotope composition. The methane carbon isotope values of the No. 9 and No. 10 coal seam joint extraction gas samples are between -46.78‰ and -46.21‰ , without showing large-scale dispersion. This observation fully demonstrates that during the on-site cross-measure borehole joint extraction process, gas from the two coal seams flows into the extraction system at a relatively stable ratio, and the mixing process is continuous and uniform, further verifying the feasibility and rationality of using the carbon isotope method to carry out layered measurement.

It is also acknowledged that the current gas sampling was conducted as a static collection. While this provides a snapshot of the gas composition, it may not fully capture the proportional fluctuations inherent in the dynamic mixing process during the production cycle. Subsequent studies will focus on long-term, continuous monitoring to characterize these temporal variations.

4.3 Calculation of Gas Contribution Proportions in Combined Extraction

Based on the established layered measurement model (Formula 4), the gas mixing ratios of the No. 9 and No. 10 coal seams were calculated. Considering the consistency and

reliability of the data, the average values of the gas component volume fractions and methane carbon isotope values from the three measuring points were selected for calculation.

The calculation parameters are as shown in Table 2.

Table 2. Average values of coal seam gas components and carbon isotopes

Coal Seam	Mean value of methane components /%	Mean methane carbon isotope value /‰
No. 9	92.27	-47.13
No. 9 and No. 10	\	-46.42
No. 10	56.63	-44.94

By substituting these parameters into the non-homogeneous linear equation system formulated for the combined extraction of No. 9 and No. 10 coal seams, the gas contribution proportions were solved using numerical calculation software. The results, as illustrated in Figure 3, demonstrate the following:

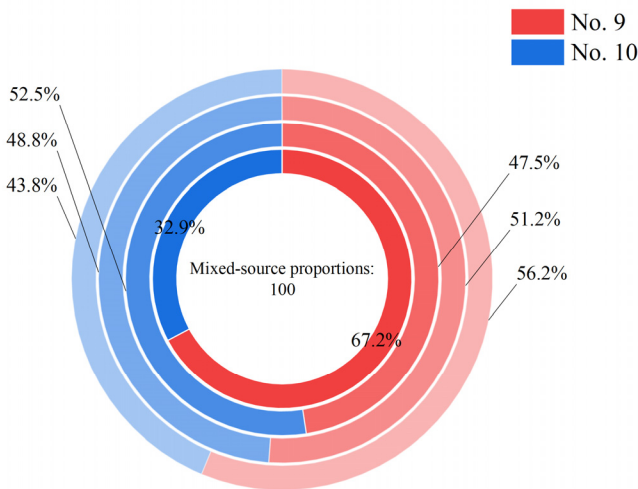


Fig. 3. Comparison of calculated results of mixed-source proportions

The calculated mixing proportions for the No. 9 coal seam across the three measuring points range from 47.53% to 67.15%, while those for the No. 10 coal seam range from 32.85% to 52.47%. This variance in the distribution range is primarily attributed to differences in borehole construction locations, geological burial conditions, borehole drilling parameters, extraction negative pressure, and spatial variations in coal seam permeability. Furthermore, because the boreholes used for individual extraction and those for combined extraction were not identical, certain fluctuations in the experimental and calculated data were inevitable.

To derive a representative result for the test area, the arithmetic mean method was applied to the data from all three measuring points. The calculated gas contribution

proportions were determined to be 56.24% for the No. 9 coal seam and 43.76% for the No. 10 coal seam. Both results fall within the range of the individual point tests, demonstrating high data consistency and representativeness. These values accurately reflect the gas source composition during the joint extraction of the No. 9 and No. 10 coal seams in the Shanjiaoshu Mine, providing a precise and reliable quantitative basis for calculating residual gas content, evaluating extraction standard compliance, and inspecting regional outburst prevention effectiveness.

While the isotope-based model provides a scientific estimation of gas contribution, it should be noted that the current results rely on a single analytical model. To further enhance the reliability of these findings, future work should incorporate cross-validation methods, such as tracer gas experiments or independent flow measurements for each seam, to establish a closed-loop verification process.

5 Conclusion

(1) A layered measurement model for comprehensive gas extraction by cross-measure boreholes in coal seam groups was constructed based on the mass conservation law of carbon isotopes, effectively addressing the technical difficulty of quantifying individual gas contributions in mixed extraction systems.

(2) Field tests confirmed that there are significant differences in methane carbon isotope values between the No. 9 and No. 10 coal seams, which serve as a reliable basis for conducting layered measurement calculations.

(3) Based on the average of the three measuring points, the gas contribution proportions were calculated as 56.24% for the No. 9 coal seam and 43.76% for the No. 10 coal seam. The results are stable and reliable, providing a scientific basis for on-site residual gas content calculation and extraction effect evaluation.

(4) The carbon isotope layered measurement method can be promoted in similar coal seam group mines. By expanding field validation in other regions, the engineering application parameter system can be further refined, comprehensively improving the precision of gas extraction management in coal seam groups.

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Disclosure of Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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