

Article

Impact of Gas Components on the Determination of Coal Mine Gas Content: A Case Study from China

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Abstract

Accurate measurement of coal seam gas content forms the core foundation for coal mine disaster prevention and coalbed methane resource development. However, as coal mining in China extends into deeper strata, multi-component gases (CH₄, CO₂, N₂, etc.) exhibit competitive adsorption effects and dynamic differentiation characteristics. These behaviors pose significant challenges to traditional measurement standards based on the “single methane-dominated system” assumption. This study systematically analyzes the competitive adsorption mechanisms of multi-component gases. By integrating gas data from major coal-producing provinces in China (such as Guizhou, Anhui, and Xinjiang), we reveal the heterogeneous distribution characteristics of gas components and their controlling factors, including coalification degree, burial depth, and maceral components. Case studies from Henan and Shanxi provinces demonstrate that neglecting the strong adsorption hysteresis of CO₂ and the rapid desorption characteristics of N₂ induces a systematic error exceeding 25% in total gas content measurements within areas high in non-methane components. To address these issues, we propose a “hierarchical measurement and real-time correction” framework for multi-component gas content. This framework categorizes gas measurement into four levels—ranging from single-component to all components—based on the complexity of geological conditions. It combines differentiated measurement with dynamic correction to improve the accuracy of gas content evaluation under complex geological conditions. This research provides a more reliable theoretical basis for gas pressure prediction and mine gas grade identification, offering substantial theoretical significance and engineering value for enhancing safety guarantees in deep coal mining.



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Keywords: coal mine gas; gas content; methane content; gas components; competitive adsorption; natural desorption method

1. Introduction

The global energy landscape is currently experiencing a structural transition toward low-carbon development. In this context, the strategic importance of coal mine gas or coalbed methane (CBM) exploration and development as a high-quality unconventional natural gas resource has grown increasingly prominent [1–3]. As a major coal producer, China possesses abundant CBM resources; specifically, the geological resources situated

at depths shallower than 2000 m total approximately 36.8 trillion cubic meters, ranking third globally [4]. However, gas serves not only as a resource but also as the primary factor underlying coal and gas outbursts and explosions. Statistical data indicate that the majority of recent coal mine accidents in China have been gas-related [5,6]. Consequently, accurately determining coal seam gas content provides the foundation for estimating CBM reserves and implementing technical measures to prevent disasters such as coal and gas outbursts [7]. For a considerable period, the measurement of gas parameters in China has predominantly relied on a theoretical framework and engineering standards centered on the “pure methane single-component” hypothesis. This system has facilitated effective applications in shallow regions and under simple geological conditions [8]. Nevertheless, as coal mining and CBM development in China expand into western regions, greater depths, complex structural zones, and multi-seam overlapping areas, the limitations of the traditional single-component measurement system have become increasingly apparent [9–11].

Extensive geological exploration and high-pressure adsorption experiments demonstrate that coalbed methane in actual mining areas usually exists as a multi-component gas mixture. Although methane dominates this mixture, it commonly contains varying proportions of carbon dioxide (CO₂), nitrogen (N₂), and ethane (C₂H₆) [12]. Within the coal matrix nanopore system, where pore sizes approach molecular dynamics scales, multi-component gases exert significant competitive adsorption effects and exhibit distinct kinetic differentiation. Molecular size variations, polar interactions, and pore structure heterogeneity jointly control the essence of these behaviors. For multi-component adsorption equilibrium issues, researchers commonly apply the extended Langmuir model or the ideal adsorbed solution theory (IAST). However, under deep, high-pressure, and heterogeneous coal conditions, these models exhibit certain limitations, primarily because they inadequately consider adsorption-induced swelling and the dynamic evolution of pore structures, while oversimplifying the differences in interactions among different gas molecules [13]. Consequently, model predictions under non-ideal conditions may deviate from actual desorption behaviors. These micro-scale competitive adsorption and heterogeneous thermodynamic characteristics not only affect the storage and enrichment patterns of gas throughout geological history, but also manifest as inconsistent release rates of different components during borehole coring and transient desorption, potentially triggering a degree of adsorption hysteresis [14]. Regarding regional distribution characteristics, coalbed gas components vary significantly across major coal-producing regions in China. Although methane remains dominant overall, areas under strong structural deformation, thermal events, or fluid activity—such as Guizhou, Anhui, and Xinjiang—exhibit relatively high proportions of CO₂ and N₂. In fact, non-methane components in the desorption gas of certain coal cores approach or even exceed methane levels [15,16]. However, the theoretical frameworks of China’s current gas content measurement methods, such as the direct method and indirect calculation method, still rely primarily on a single-component assumption [17,18]. When estimating lost and residual gas under non-methane enriched conditions, researchers might introduce systematic deviations into the calculated gas content if they fail to account for two factors: the desorption hysteresis effect caused by the stronger adsorption capacity of CO₂ on the coal surface, and the preferential dissipation behavior driven by the higher diffusion rate of N₂ within the fracture network [19]. Previous studies indicate that the presence of multi-component gases significantly influences the inversion results of gas content and gas pressure when using indirect methods [20]. Furthermore, within a calculation system that uses methane as the sole calibration gas, compositional differences can bias gas emission predictions and gas outburst risk grading, creating misjudgment risks in CO₂-enriched or N₂-anomalous zones [21]. Therefore, complex gas components necessitate applicability modifications and extensions of existing single-component measurement and

inversion methods to improve the reliability of gas parameter evaluations under complex geological conditions.

Based on the current research status, this study evaluates the model applicability issues that arise during the measurement of multi-component gas. As shown in Figure 1, we first analyze the competitive occupancy behavior of non-methane components within micropores at the microscopic level, along with their mechanisms of influence on gas–solid phase equilibrium. Second, using gas data from major coal-producing provinces in China, we investigate the impacts of coalification degree, burial depth, and maceral components. Finally, we discuss the deficiencies of China’s current gas content measurement methods and, on this basis, propose a scientific, transparent, and highly adaptable multi-component gas content measurement system. This framework aims to provide robust theoretical support for the safe mining of deep coal and the efficient evaluation of resources.

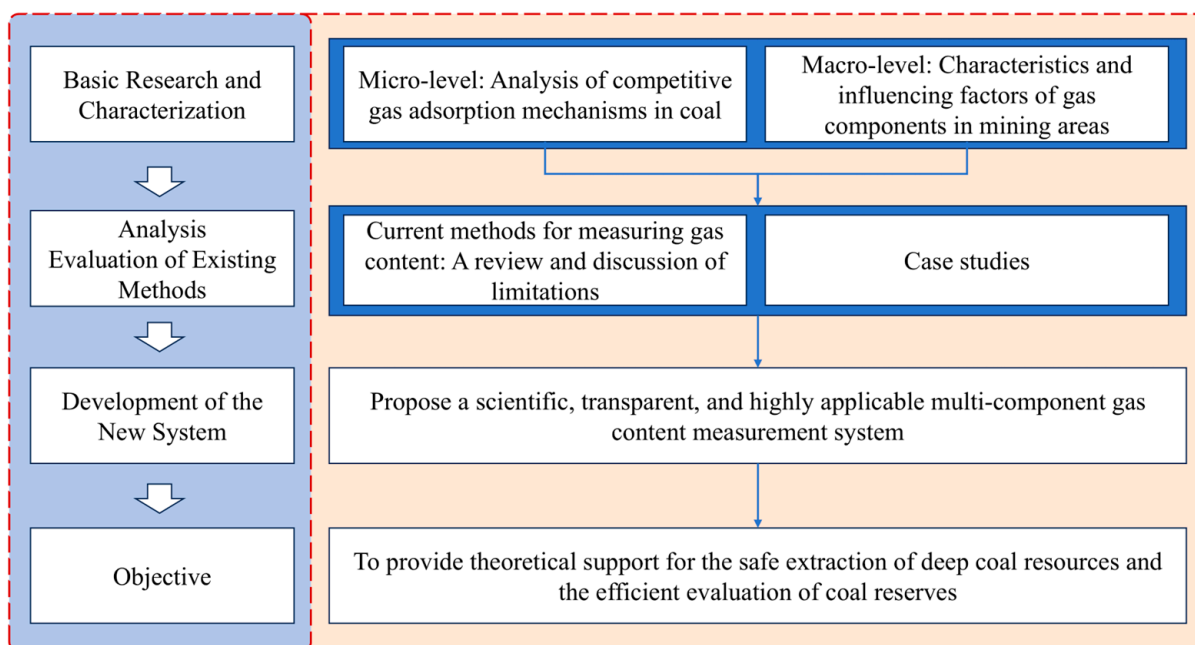


Figure 1. Technical flowchart of the study.

2. Occurrence State of Coal Gas

Gas exists within the coal body in two primary states—free gas and adsorbed gas—with the latter typically accounting for more than 80% of the total volume [22]. As illustrated in Figure 2, free gas moves freely within the fractures and pores inside the coal body, whereas the surfaces and interior of the coal matrix generally retain adsorbed gas. Under the influence of various forces, gas molecules can migrate between the coal matrix and the pore-fracture system, undergoing reversible processes of adsorption and desorption. When defining gas as a single-component system, its adsorption behavior on the coal surface generally conforms to the Langmuir equation.

$$V = \frac{V_L b P}{1 + b P} \quad (1)$$

where V is the gas adsorption capacity (cm^3/g); V_L represents the maximum gas adsorption capacity (cm^3/g); b denotes the adsorption constant (MPa^{-1}); and P is the gas pressure (MPa).

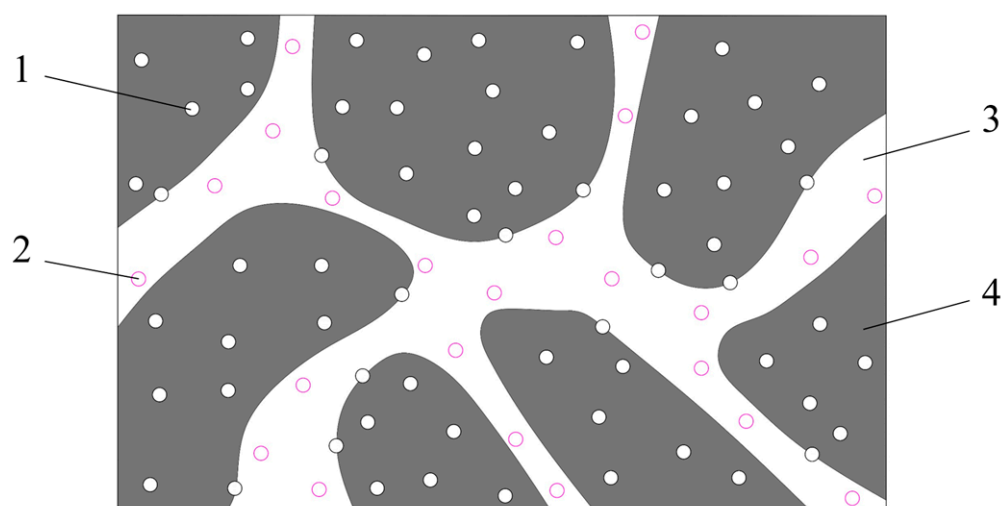


Figure 2. Occurrence states of coal seam gas. 1—adsorbed gas; 2—free gas; 3—pores and fractures; 4—coal matrix.

It is noteworthy that gas is primarily composed of methane, along with ethane, propane, higher-order hydrocarbons, and several incombustible gases such as carbon dioxide, hydrogen sulfide, nitrogen, and helium. The three most prevalent gas molecules are CH_4 , CO_2 , and N_2 . In multi-component systems, porous media exhibit selective gas adsorption [23]. Experimental evidence suggests that under constant pressure and temperature, the adsorption capacity of coal for these components generally follows the sequence: $\text{CO}_2 > \text{CH}_4 > \text{N}_2$ [24]. Consequently, in a multi-component coexisting system, CO_2 preferentially occupies high-energy adsorption sites, displacing CH_4 molecules to lower-energy sites or into the fracture network. Moreover, the heterogeneous pore development within coal includes both macropores and micropores. The molecular diameters of CH_4 , CO_2 , and N_2 are 0.38 nm, 0.33 nm, and 0.36 nm, respectively, indicating that CO_2 and N_2 molecules can penetrate micropores more readily than CH_4 for adsorption [25]. The adsorption volume of an individual gas within a mixture can be described using the Extended Langmuir (E-L) model, which determines the adsorption capacity of each component based on their respective partial pressures. The expression is given by:

$$V_i = \frac{V_{L,i} b_i P_i}{1 + \sum_{j=1}^n b_j P_j} \quad (2)$$

where V_i is the adsorption capacity of component i (cm^3/g); $V_{L,i}$ represents the maximum adsorption capacity (Langmuir volume) of component i (cm^3/g); b_i is the adsorption constant of component i ; P_i is the partial pressure of component i (MPa); and n denotes the total number of components.

In addition to the E-L model presented in Equation (2), other existing adsorption capacity calculation models include the Langmuir–Freundlich (L-F) and Modified Langmuir (M-L) models [26], as summarized in Table 1. The competitive adsorption of multi-component gases in coal seams represents a complex scientific challenge. Comparisons demonstrate that the L-F model, by incorporating a heterogeneity factor into the E-L framework, effectively mitigates previous theoretical limitations. Furthermore, compared to the more complex M-L and Modified Redlich–Peterson (M-R-P) models, the L-F model exhibits optimal scientific utility.

Table 1. Common gas adsorption models.

No.	Model	Equation	Characteristics
1	E-L model	$Q_i = \frac{Q_{max,i} b_i p_i}{1 + \sum_{j=1}^n b_j p_j}$	Assumes a homogeneous surface where adsorption sites are equivalent, independent, and energetically identical, neglecting interactions between adsorbate molecules.
2	L-F model	$Q_i = \frac{Q_{m,i} (b_i p_i)^{q_i}}{1 + \sum_{j=1}^n (b_j p_j)^{q_i}}$	Incorporates a heterogeneity factor expression into the E-L framework to reduce its theoretical limitations.
3	M-L model	$Q_i = \frac{Q_{m,i} b_i \left(\frac{p_i}{\eta_i}\right)}{1 + \sum_{j=1}^n K_j \left(\frac{p_j}{\eta_j}\right)}$	Explores interaction terms and component-specific site affinities, enabling the description of synergistic adsorption behaviors.
4	E-F model	$Q_1 = \frac{k_1 C_1^{\left(\frac{1}{\eta_1}\right)+x_1}}{C_1^{x_1} + y_1 C_1^{z_1}} \quad Q_2 = \frac{k_2 C_2^{\left(\frac{1}{\eta_2}\right)+x_2}}{C_2^{x_2} + y_2 C_1^{z_2}}$	An empirical power-law equation primarily used to characterize multilayer adsorption on heterogeneous surfaces.
5	M-R-P model	$Q_i = \frac{a_i \left(\frac{C_i}{\eta_i}\right)}{1 + \sum_{j=1}^n b_j \left(\frac{C_j}{\eta_j}\right)^{\beta_j}}$	Introduces a heterogeneity factor and integrates the advantages of the Langmuir and Freundlich models; it adheres to Henry's Law at low pressures while characterizing the heterogeneous adsorption properties of coal samples.

3. Characteristics of Gas Components in Major Chinese Mining Areas

Treating heavy hydrocarbon gases (C_{2+}) as a single category, the primary components of CBM include CH_4 , C_{2+} , CO_2 , and N_2 . In the United States, the components are ranked as follows: $CH_4 > CO_2 > C_{2+} > N_2$ [27]. In contrast, the ranking of gas components in China, excluding CH_4 , differs from that in the U.S. Based on investigation data from the thesis by Xu [15], the gas components in major Chinese mining areas have been classified as shown in Table 2.

Overall, coal mine gas in China is dominated by CH_4 , with concentrations typically ranging from 80% to 99%. However, CH_4 content fluctuates significantly across different regions and mines; notably, in coal core desorption gas, it can drop below 10%. In certain mining areas, N_2 and CO_2 occupy high proportions, sometimes even exceeding CH_4 , reflecting the complexity of gas genesis and preservation conditions. While the overall C_{2+} content is low (generally 0–7%), it exceeds 30% in specific mines (reaching up to 32.13%), indicating strong localized hydrocarbon enrichment. In summary, Chinese CBM is characterized by CH_4 as the primary constituent, with significant variations in N_2 and CO_2 ratios and localized anomalies in heavy hydrocarbons.

The significant variation in gas component proportions across different regions fundamentally results from the multi-scale coupling of coalification (coal rank), burial conditions (burial depth), and maceral characteristics (Figure 3). Regarding coal rank control and thermal evolution effects, as the coalification degree increases, the generation and adsorption capacity of CH_4 gradually strengthen and dominate. Conversely, CO_2 exhibits a declining trend because oxygen-containing functional groups decrease and the coal structure densifies, whereas C_{2+} reach a relative peak during the medium-coal-rank stage before gradually decreasing [28–30]. This evolutionary trend partially explains why high-coal-rank regions exhibit high methane enrichment, such as Shanxi (where produced gas generally ranges from 83% to 99%), Guizhou (where most mines range between 90% and 99%), and Liaoning (mostly ranging from 84% to 99%). In contrast, methane content fluctuates widely in Henan (56–98%), Inner Mongolia (55–99%), and Xinjiang (ranging from 7% to 96%), indicating a wide span of coal rank distribution and heterogeneous local thermal evolution. This heterogeneity leads to differentiated residual and release characteristics of CO_2 across

various coal ranks, as seen in regional variations, such as 1–11% in Shanxi, 2–8% in Inner Mongolia, and up to 15% in Henan.

Table 2. Gas components in major Chinese mining areas.

Province	Mine ID	Gas Type	CH ₄ (%)	C ₂₊ (%)	N ₂ (%)	CO ₂ (%)	Other Gases (%)
Guizhou	Mine 1	①	95.46–96.41	2.21–3.08	0.95–1.45	0.10–0.35	0.03–0.09
	Mine 2		98.41–99.09	0.06–0.07	0.38–1.07	0.35–0.82	0.01–0.07
	Mine 3		91.37	6.71	1.78	0.03	0.11
	Mine 4	②	20.49–98.81	N/A	0.67–79.32	0.00–4.28	N/A
	Mine 5	①	79.60–86.70	0.08–0.23	3.00–12.80	4.60–9.80	0.00–0.07
	Mine 6	②	72.24–98.23	0.01–23.22	0.70–16.51	0.01–4.05	N/A
Anhui	Mine 1	①	16.2–96.68	0.35–32.13	0.13–74.72	1.62–27.26	N/A
	Mine 2		55.10–91.73	N/A	1.07–18.22	1.51–56.89	N/A
	Mine 3		54.12–97.95	0.01–0.58	0.00–14.33	0.86–44.48	N/A
	Mine 4		97.36–98.95	0.02–0.04	0.25–0.78	0.55–2.36	N/A
Shanxi	Mine 1	②	95.9–99.4	0.008–0.038	0.31–3.75	0.14–0.40	0.015–0.042
	Mine 2		27.82–89.41	N/A	6.55–72.20	N/A	N/A
	Mine 3		83.79–97.57	0.00–0.46	0.86–14.13	1.47–4.71	N/A
	Mine 4		87.18–96.28	N/A	2.95–10.39	0.77–2.41	N/A
	Mine 5		83.83–86.83	0.01–0.04	4.99–11.13	8.10–9.28	N/A
	Mine 6		60.50–96.08	0.02–0.04	1.68–30.31	0.29–11.28	N/A
	Mine 7		95.90–99.40	0.008–0.038	0.31–3.75	0.14–0.40	0–0.057
Liaoning	Mine 1	②	97–99	N/A	9.49	3.22	N/A
	Mine 2	①	67.4–94.29	N/A	N/A	N/A	N/A
	Mine 3	②	84.57–96.42	N/A	2.29–15.41	0.02–1.29	N/A
Henan	Mine 1	①	75.67–97.65	N/A	0.00–24.20	1.07–14.95	N/A
	Mine 2	②	56.07–98.55	0.05–24.26	0.00–33.53	0.53–10.23	N/A
Xinjiang	Mine 1	①	79.98–93.29	0.69–4.66	1.83–14.58	0.30–0.79	N/A
	Mine 2		81.91–93.32	0.76–5.36	2.18–9.45	0.04–0.28	N/A
	Mine 3	②	67.22–92.73	0–2.63	0.06–19.78	6.48–27.95	N/A
	Mine 4		86.53–96.28	0.02–6.69	0.16–10.73	0.98–10.44	N/A
	Mine 5	①	73.07–89.24	0.20–1.71	1.03–4.51	7.59–21.68	N/A
	Mine 6		7.67–94.50	N/A	0.00–57.11	0.26–87.14	N/A
Inner Mongolia	Mine 1	②	55.14–99.06	0–1.30	0.45–43.25	0.18–2.48	N/A
	Mine 2	①	59.94–93.91	0.010–0.060	2.202–37.90	0.845–7.95	N/A
	Mine 3		88.01–97.95	0.00–0.03	1.26–10.73	0.04–2.38	N/A

Note: ① denotes produced gas, and ② denotes coal core desorption gas.

In terms of burial depth zonation and tectonic disturbance, conventional theory posits that shallow coal seams primarily contain CO₂ and N₂, whereas deep coal seams predominantly contain CH₄, with non-hydrocarbon gases decreasing overall as burial depth increases. However, measured data reveal that this pattern deviates to some extent across different mining areas. Atmospheric infiltration into shallow coal seams, poor preservation conditions, and localized tectonic fracture development likely cause the significant fluc-

tuations of N_2 in desorbed gas from coal cores in Guizhou (up to 79.32%), Anhui (up to 74.72%), Shanxi (up to 72.21%), Xinjiang (up to 57.11%), Inner Mongolia (up to 43.25%), and Henan (up to 33.53%) [31,32]. Meanwhile, certain mines in Anhui (CO_2 exceeding 50%) and Xinjiang (maximum CO_2 exceeding 80%) exhibit anomalous CO_2 enrichment. This phenomenon suggests that, beyond burial depth control, multiple factors such as fault structure conduction and microbial activity may jointly influence gas distribution, though researchers must further constrain and analyze the primary controlling mechanisms.

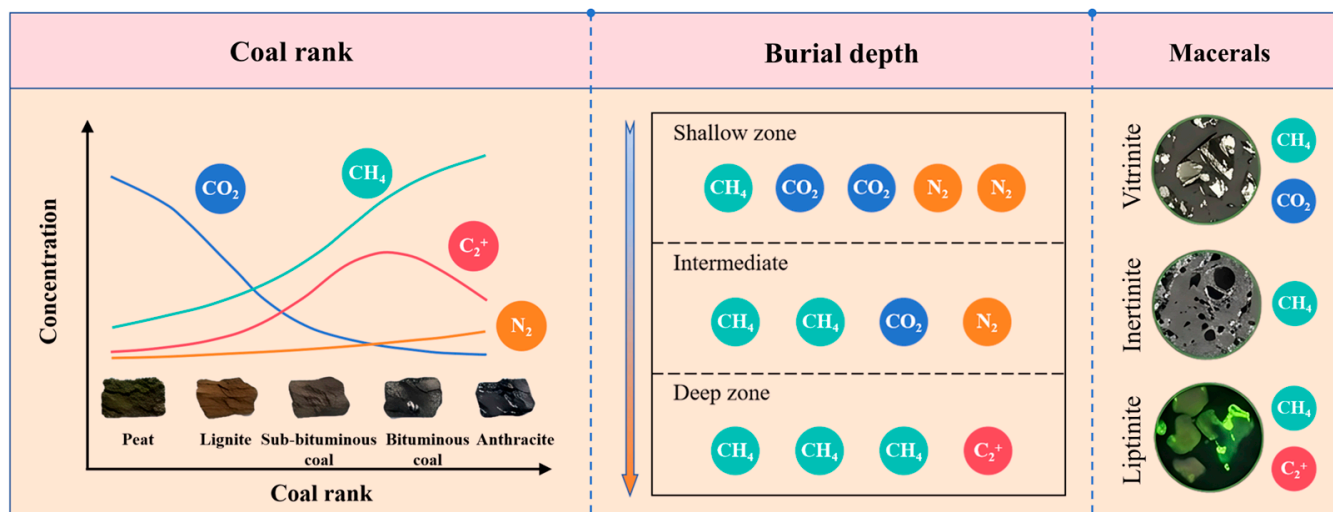


Figure 3. Impact of coal rank, burial depth, and macerals on coal gas components.

Regarding maceral characteristics, vitrinite serves as the primary adsorption carrier for gases in high-methane regions (such as Shanxi and Guizhou) due to its well-developed microporous structure and abundant oxygen-containing functional groups [33]. However, maceral heterogeneity also influences multi-component gas distribution. The large fluctuations of N_2 and free gas in Xinjiang, Inner Mongolia, and Anhui may relate to higher inertinite proportions and their relatively developed macroporous structures, which provide storage space for non-hydrocarbon gases [34]. Additionally, variations in heavy hydrocarbons and multi-component gases in regions like Liaoning (where N_2 partially exceeds 15% and CO_2 remains low) and Henan may correlate with exinite enrichment and its control over C_{2+} generation and pore evolution [35].

In conclusion, the regional variations and localized anomalous distributions of gas components across China's major mining areas do not stem from a single controlling factor. Instead, they represent a multi-factor coupled response shaped by the collective effects of coal-rank thermal evolution, variations in burial-tectonic conditions, and maceral heterogeneity, with different factors displaying varying degrees of dominance and superposition across different regions.

4. Current Standards for Gas Content Measurement in China

4.1. Standards for Measuring Gas Content

Current Chinese standards for measuring gas content include the GB/T 23250-2009 [17] and the GB 41022-2021 [18]. Corresponding information, such as standard numbers, titles, and measurement methods, is summarized in Table 3. Notably, only the two standards released in 2009 account for the calculation of gas components; the remaining standards do not address the influence of gas components or specific measurement methodologies. This lack of differentiation reflects a broader industry-wide tendency to treat total gas content (comprising multiple gases) and CH_4 content as synonymous. Furthermore, the majority

of research literature concerning gas outbursts neglects to provide a detailed analysis of individual gas components.

Table 3. List of gas content measurement standards.

No.	Standard Number	Standard Title	Measurement Method	Characteristics	Gas Components Considered (Yes/No)
1	GB/T 23249-2009 [36]	Method for Determination of Coal Seam Gas Content during Geological Exploration	Natural desorption + degassing	Coal core tube sampling; measurements taken at the sampling site and laboratory; results represent the cumulative total of different gas components.	Yes
2	GB/T 23250-2009 [17]	Direct Underground Measurement Method of Coal Seam Gas Content	Natural desorption + degassing; natural desorption	Fixed-point sampling via device; measurements taken at the site and laboratory; results represent the cumulative total.	Yes, but C ₂₊ is excluded
3	GB/T 28753-2012 [37]	Method for Determination of Coalbed Methane Content by Heating Desorption	Natural desorption + heating desorption	Coal core tube sampling; natural desorption at site and heating desorption in laboratory; results represent the cumulative total.	No
4	GB/T 35053-2018 [38]	Method of Sealed Coring for Determination of Coalbed Methane Content	Natural desorption after sealed coring	Consistent with GB/T 28753-2012.	No
5	GB/T 19559-2021 [39]	Method for Determination of Coalbed Methane Content	Natural desorption after sealed coring	Consistent with GB/T 28753-2012.	No
6	GB 41022-2021 [18]	Basic Indicators of Coal Mine Gas Drainage	Back-calculation method	Measured gas pressure is used to back-calculate gas content via established formulas.	No
7	NB/T 11329-2023 [40]	Underground One-stop Automated Measurement Method of Coal Seam Gas Content	Natural desorption	Uses integrated instruments for full underground measurement; provides direct data output.	No
8	NB/T 11755-2024 [41]	Underground Rapid Measurement Method of Coal Seam Gas Content	Natural desorption	Consistent with NB/T 11329-2023.	No

The measurement of gas content is categorized into direct and indirect methods, where the former involves collecting coal cores or cuttings underground to determine coal seam gas content while the latter relies on the measurement of gas pressure. As the most common approach, the direct method primarily consists of natural desorption and degassing. Natural desorption determines gas content by allowing coal samples to

release gas naturally under atmospheric pressure and subsequently desorb gas in a crushed state, categorizing the total volume into five parts: lost gas volume (A_1), underground desorbed gas volume (A_2), pre-crushing desorbed gas volume (A_3), post-crushing desorbed gas volume (A_4), and non-desorbed gas volume (A_5). In contrast, the degassing method utilizes a vacuum system combined with heating to forcibly extract adsorbed gas from the coal samples, comprising four components: lost gas volume (B_1), underground desorbed gas volume (B_2), degassed gas volume before crushing (B_3), and degassed gas volume after crushing (B_4). The procedural differences between these methods are illustrated in Figure 4. The fundamental distinction between natural desorption and degassing lies in the determination of non-desorbed gas, as the former requires estimation via theoretical models while the latter is obtained directly through experimentation. From the perspective of result accuracy, the degassing method is significantly superior to natural desorption because physical extraction minimizes systemic theoretical errors arising from variations in coal types.

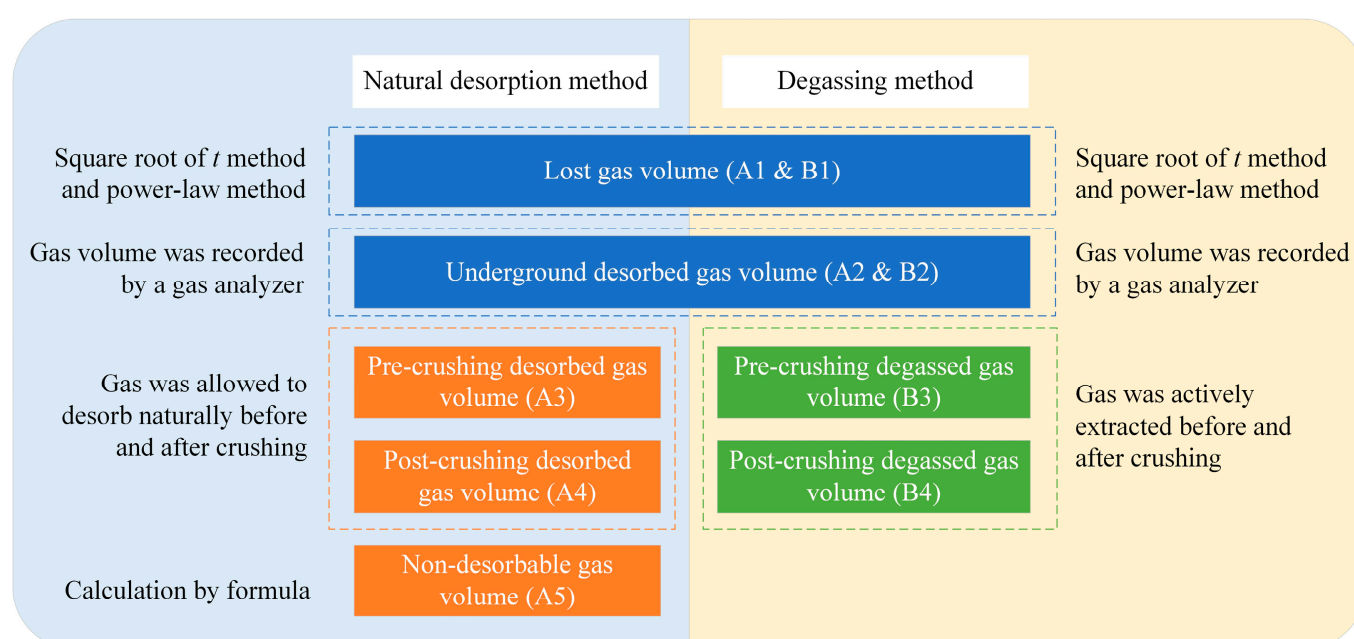


Figure 4. The distinction between the natural desorption method and the degassing method.

Lost gas content refers to the volume of gas that escapes into the surrounding environment during the period between a coal sample's detachment from the coal body and its placement into a sealed canister. Regardless of the specific regulatory standards applied, researchers utilize theoretical models to calculate this lost gas content, as summarized in Table 4. Currently, the most prevalent approach is the $\sqrt{t}$ method [42], which represents an improvement of the USBM direct method originally developed by the United States Bureau of Mines [43]. This method operates on the principle that gas desorption adheres to Fick's laws of diffusion, creating a linear, proportional relationship between the initial volume of desorbed gas and the square root of time; researchers then apply linear regression to determine the total gas loss. Conversely, the power function method relies on empirical data statistics and posits that the desorbed gas volume is proportional to time raised to a power, making it highly suitable for cases where the $\sqrt{t}$ method fails to yield an adequate fit.

Table 4. Two calculation methods for lost gas volume.

Dimension	$\sqrt{t}$ Method (USBM Method)	Power Function Method
Theory	Based on Fick's Law of diffusion, it assumes that early-stage gas diffusion is primarily driven by concentration gradients.	Based on statistical patterns from extensive experimental data, it assumes the desorption process can be described by a general mathematical power function.
Assumption	Desorption volume is strictly proportional to the square root of time.	Desorption volume is proportional to time raised to a specific power, with the exponent determined by coal sample characteristics.
Formula	$V_1 = a + b \cdot \sqrt{t}$	$V_1 = q_0 \left[\frac{(1+T_0)^{1-n} - 1}{1-n} \right]$
Applicability	Suitable for coal samples with short desorption times and relatively homogeneous coal properties.	Suitable for scenarios where the $\sqrt{t}$ method exhibits significant curvature and fails to achieve a linear fit.

Taking the atmospheric natural desorption method as an example, researchers must determine four additional distinct gas content components alongside the lost gas volume: underground desorbed gas, pre-crushing desorbed gas, post-crushing desorbed gas, and non-desorbed gas. First, field personnel use an underground sealed sampler to collect coal cuttings from a borehole. By connecting the sample to a portable underground desorbed gas analyzer or a graduated cylinder, operators employ the water displacement method to measure the real-time volume of gas naturally released by the sample, which yields the underground desorbed gas volume, V_2 . Second, once the samples arrive at the surface laboratory, technicians place the sealed canister containing the sample into a constant-temperature water bath without altering the natural particle size of the coal. They then connect the system to a laboratory automated desorption analyzer and maintain this setup until bubbles cease to emerge from the measuring tube, thereby determining the pre-crushing desorbed gas volume, V_3 . Third, researchers transfer the coal sample into a specialized sealed vacuum ball mill for mechanical pulverization. This process breaks down the micro-pore structure of the coal to compel the complete release of locked, deep-seated gas, allowing the connected measuring tube to record this specific gas volume as the post-crushing desorbed gas volume, V_4 . Finally, laboratory personnel collect the gas desorbed at the surface and perform chromatographic analysis according to the standard procedures in GB/T 13610-2020 [44]. This analysis yields the individual gas components within the gas mixture, providing the respective concentrations for $C(N_2)$, $C(CH_4)$, $C(CO_2)$, and $C(C_{2+})$.

$$\begin{cases} D(N_2) = \frac{C(N_2) - 3.57C(O_2)}{100 - 4.57C(O_2)} \times 100 \\ D(CH_4) = \frac{C(CH_4)}{100 - 4.57C(O_2)} \times 100 \\ D(CO_2) = \frac{C(CO_2)}{100 - 4.57C(O_2)} \times 100 \\ D(C_{2+}) = \frac{C(C_{2+})}{100 - 4.57C(O_2)} \times 100 \end{cases} \quad (3)$$

where $D(N_2)$, $D(CH_4)$, $D(CO_2)$, and $D(C_{2+})$ represent the respective concentrations of each gas component after deducting the air content (%).

Researchers calculate the volume of a specific gas during each of the aforementioned processes using the following equation:

$$V_i^j = \frac{V_j \times D(x)}{100}, j = 1, 2, 3, 4 \quad (4)$$

where V_i^j represents the volume of a specific gas within the mixed gas converted to standard conditions (cm^3); V_j represents the gas volume during a specific process (cm^3); and $D(x)$ represents the concentration of a specific gas within the coal seam gas components (%).

Technicians determine the coal sample gas content for each individual stage using the following equation:

$$A_i = \frac{\sum V_i}{m}, i = 1, 2, 3, 4 \quad (5)$$

where A_i represents the coal sample gas content at each stage (cm^3/g); m represents the mass of the coal sample (g); and V_i represents the volume of a specific gas at each stage (cm^3).

Regarding the non-desorbed gas volume at atmospheric pressure, A_5 , this term refers to the residual gas volume that remains trapped within the coal sample even after mechanical pulverization and desorption. Analysts generally compute this value using the following formula:

$$A_5 = \frac{0.1ab}{1 + 0.1b} \times \frac{100 - A_d - M_{ad}}{100} \times \frac{1}{1 + 0.31M_{ad}} + \frac{\varphi}{\gamma} \quad (6)$$

where A_5 is the non-desorbed gas volume of the coal under standard atmospheric pressure (cm^3/g); a represents the gas adsorption constant of the coal, denoting the maximum adsorption capacity of the coal at the experimental temperature (cm^3/g); b represents the gas adsorption constant (MPa^{-1}) of the coal; A_d represents the ash content of the coal (%); M_{ad} represents the moisture content of the coal (%); φ represents the porosity of the coal (cm^3/cm^3); and γ represents the bulk density of the coal (g/cm^3).

4.2. Limitations of the Current Standard

In the atmospheric natural desorption method, the impact of gas components on A_1 is primarily manifested in the varying diffusion coefficients of different components. N_2 , characterized by a small molecular weight and extremely low adsorption potential, escapes rapidly from macropores and fractures during the initial exposure stage. Consequently, a high N_2 content in a coal seam increases the slope of the measured initial desorption curve; if extrapolated using a CH_4 -based diffusion model, the total value of A_1 will be significantly overestimated. Conversely, although CO_2 has a small molecular diameter, its strong adsorption hinders migration within micropores, resulting in significant release hysteresis. For high- CO_2 coal seams, the initial desorption volume may be smaller, leading to an underestimated A_1 value during extrapolation. The influence of gas components on A_2 and A_3 is largely driven by the fact that the solubility of CO_2 in water is more than 20 times that of CH_4 . When employing the water displacement method for A_2 measurement underground, substantial CO_2 dissolution in the measuring cylinder causes recorded volumes to be markedly lower than actual release levels. Furthermore, borehole water accumulation can significantly alter CO_2 escape patterns. Regarding A_4 , the proportions of heavy hydrocarbons and CO_2 are typically higher than in the A_2 stage because these molecules exhibit higher filling densities in micropores. Ignoring this variation by relying solely on early-stage components analysis will underestimate the actual heavy hydrocarbon and CO_2 content throughout the process. Finally, the impact on A_5 is reflected in its dependence on a and b values; the a value of CO_2 is typically 2–3 times that of CH_4 , while its b value is higher by an order of magnitude. Furthermore, coal exhibits a stronger retention capacity for CO_2 under atmospheric pressure. Consequently, simply applying Equation (6) without accounting for component differences will result in an estimation error for A_5 .

5. Case Study

To further illustrate how gas components affect each stage and the final results of gas content measurements, this case study analyzes a mine in Henan Province (hereafter “Mine H”) from reference [45] and a mine in Shanxi Province (hereafter “Mine S”) from reference [46]. Tables 5 and 6 present the specific gas component proportions and total gas contents for five locations in Mine H and three locations in Mine S, respectively. Because the original literature does not detail the gas content for each specific process, this analysis applies an empirical distribution ratio of $A_1 \approx 20\%$, $A_2 \approx 35\%$, $A_3 \approx 15\%$, $A_4 \approx 20\%$, and $A_5 \approx 10\%$. Data in Tables 5 and 6 indicate that while CH_4 volume fractions are the highest and CO_2 volume fractions are the lowest in both mines, their gas content distributions differ significantly. Total gas content in Mine S is highly concentrated, whereas Mine H exhibits an uneven distribution (e.g., $2.64 \text{ m}^3/\text{t}$ at Location H-1 compared to $16.13 \text{ m}^3/\text{t}$ at Location H-2).

Table 5. Gas components and content at five locations in a mine of Henan Province [45].

Location ID	Gas Volume Fraction (%)				Gas Content ($\text{m}^3 \cdot \text{t}^{-1}$)			
	CO_2	N_2	CH_4	Total	A_1	$A_2 + A_3$	A_4	A_5
H-1	10.11	30.75	59.14	2.64	0.53	1.32	0.53	0.26
H-2	2.52	14.84	82.64	16.13	3.23	8.07	3.23	1.61
H-3	6.96	36.77	56.27	6.57	1.31	3.29	1.31	0.66
H-4	2.83	5.11	92.06	9.24	1.85	4.62	1.85	0.90
H-5	1.67	33.82	64.51	5.19	1.04	2.60	1.04	0.52

Table 6. Gas components and content at three locations in a mine of Shanxi Province.

Location ID	Gas Volume Fraction (%)				Gas Content ($\text{m}^3 \cdot \text{t}^{-1}$)			
	CO_2	N_2	CH_4	Total	A_1	$A_2 + A_3$	A_4	A_5
S-1	7.63	16.37	76.00	3.38	0.68	1.69	0.68	0.34
S-2	1.89	13.02	85.09	3.86	0.77	1.93	0.77	0.39
S-3	8.74	41.26	50.00	2.84	0.57	1.42	0.57	0.28

Tables 7 and 8 present the gas contents after applying the analytical and compositional considerations described above. The corrected results demonstrate that accounting for the combined effects of multi-component gases significantly increases the total gas content at all locations in Mine H, with increments ranging from 4.40% to 25.60%. Locations H-1 and H-3, which feature the highest proportions of non-methane gases, show gas content corrections of 25.00% and 25.60%, respectively. Conversely, Location H-4, which exhibits the highest CH_4 volume fraction (92.06%), shows an increase of only 4.40%. The Safety Regulations in Coal Mines [47] mandates that coal seams with a gas content exceeding $8.0 \text{ m}^3/\text{t}$ are classified as outburst-prone. Consequently, regulatory bodies would have identified Location H-3 as a non-outburst seam before the adjustment; however, its corrected gas content exceeds $8.0 \text{ m}^3/\text{t}$, which reclassifies it as an outburst seam. This comparison reveals that ignoring the adsorption contributions of CO_2 and N_2 during conventional measurements severely underestimates gas content in zones with high non-methane gas concentrations. Therefore, incorporating a multi-component coupling correction is a prerequisite for ensuring scientific data integrity and production safety in mine gas control and resource evaluation. Furthermore, Mine S exhibits a similar upward trend after introducing the multi-component correction, with the total gas content across all locations increasing by 8.30% to 26.10% compared to the original values. Locations S-1 and S-3, where non-methane gases exert a significant influence, show substantial corrected increases of 24.90%

and 26.10%, respectively, whereas the increment at Location S-2—which holds the highest original content—converges to 8.30%.

Table 7. Gas content after component correction at the mine H.

Location ID	Original Gas Content ($\text{m}^3 \cdot \text{t}^{-1}$)	Corrected Gas Content ($\text{m}^3 \cdot \text{t}^{-1}$)					Growth Rate (%)
		A_1	$A_2 + A_3$	A_4	A_5	Total	
H-1	2.64	0.69	1.41	0.62	0.58	3.30	25.00
H-2	16.13	3.55	8.35	3.39	2.52	17.81	10.40
H-3	6.57	1.84	3.48	1.48	1.45	8.25	25.60
H-4	9.24	1.94	4.67	1.89	1.15	9.65	4.40
H-5	5.19	1.40	2.59	1.06	0.68	5.73	10.40

Table 8. Gas content after component correction at the mine S.

Location ID	Original Gas Content ($\text{m}^3 \cdot \text{t}^{-1}$)	Corrected Gas Content ($\text{m}^3 \cdot \text{t}^{-1}$)					Growth Rate (%)
		A_1	$A_2 + A_3$	A_4	A_5	Total	
S-1	3.38	0.81	1.69	0.74	0.98	4.22	24.90
S-2	3.86	0.83	1.94	0.79	0.62	4.18	8.30
S-3	2.84	0.80	1.45	0.64	0.69	3.58	26.10

The corrected data from the various locations across both mines reveal two primary distinct characteristics. First, a negative correlation exists between the percentage increase and the original gas content. Specifically, regions with lower original gas content and an enrichment of non-methane gases (such as H-1, H-3, S-1, and S-3) exhibit corrected increments that approach or exceed 25%, whereas regions dominated by methane with high original content (such as H-2, H-4, and S-2) show markedly suppressed increases. Second, spatial occurrence exhibits significant heterogeneity. The data from Mine H span a wide range and include extreme high-value points, such as H-2, which reaches a corrected total content of $17.81 \text{ m}^3/\text{t}$. In contrast, the corrected total gas content for Mine S remains relatively low and tightly clustered between $3.58 \text{ m}^3/\text{t}$ and $4.22 \text{ m}^3/\text{t}$. These variations reflect the unique gas component characteristics and gas accumulation patterns inherent to different mining areas and coal seams.

6. Framework Development for “Hierarchical Measurement and Real-Time Correction” of Gas Content

Addressing the complexities of coal seam gas occurrence under deep mining conditions, alongside the limited applicability and accuracy of traditional gas content measurement methods, this paper establishes a “hierarchical measurement–real-time correction” multi-component gas content measurement framework. This system builds upon the analysis results from the preceding sections and aligns with the application priorities of the gas content concept across diverse engineering scenarios. Depending on specific coal seam geological conditions and gas component characteristics, the framework targets and matches four distinct measurement levels: single-component, three-component, four-component, and full-component. Furthermore, the system enhances the accuracy of gas content measurements through dynamic component monitoring and real-time corrections. Figure 5 illustrates the overall architecture of this framework.

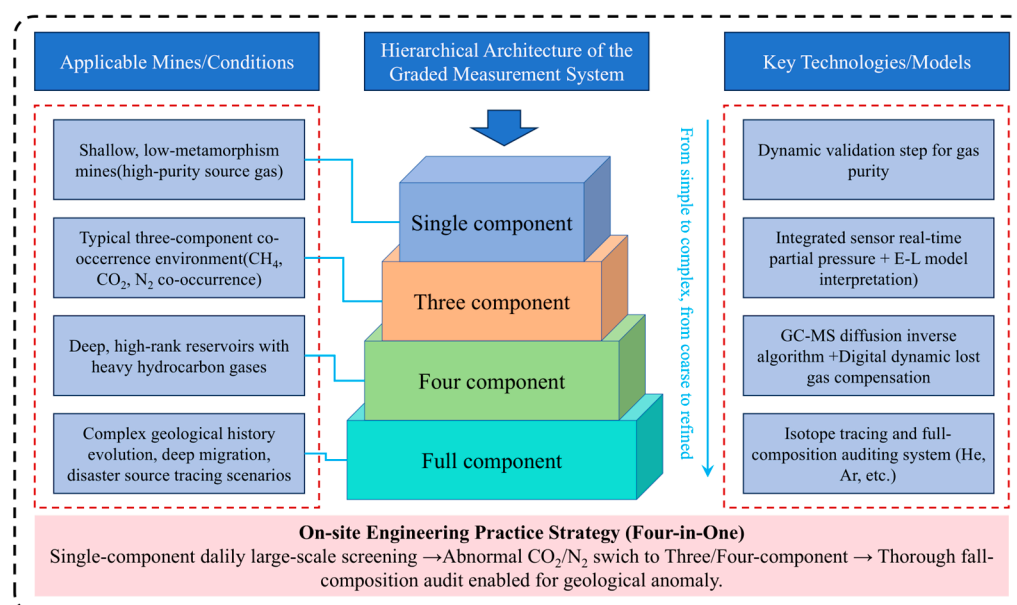


Figure 5. A new framework for measuring gas content based on the “Four-in-One” model.

The single-component tier primarily applies to shallow mining zones characterized by low metamorphism and relatively uniform gas sources (e.g., Mine 2 in Guizhou Province and Mine 1 in Shanxi Province in Table 2, where CH_4 concentration exceeds 95%). During field implementation, while following the national standard desorption process, this level requires underground explosion-proof sampling devices to maintain a state as close to the original reservoir pressure as possible and restrict pressure fluctuations within a reasonable range, thereby reducing gas dissipation errors during sampling. Concurrently, the system introduces a “dynamic gas purity verification” stage, utilizing a periodic continuous sampling method during the initial desorption phase and a portable infrared sensor for rapid purity screening at the final desorption phase. If non-methane components consistently remain below 5%, the conventional single-component calculation model remains applicable. At the level of real-time correction algorithms, this tier incorporates the Peng–Robinson real gas equation of state based on the conventional ideal gas assumption to correct gas deviations under high-pressure conditions. By integrating the attractive and repulsive correction constants alongside field-measured gas pressure and absolute ambient temperature, this equation dynamically resolves the compressibility factor and corrects the measured volume to standard state volume, which significantly enhances the accuracy of gas content calculations.

The three-component tier specifically targets the widespread CH_4 – CO_2 – N_2 co-occurrence zones in China (e.g., Mine 2 in Anhui Province and Mine 5 in Guizhou Province in Table 2). In these mining areas, multi-component co-occurrence can trigger significant competitive adsorption effects, causing traditional single-component measurement methods to miscalculate gas reserves. During field deployment, engineers can utilize intelligent pressure-measuring desorption devices integrated with CO_2 and N_2 sensors to periodically capture the partial pressure and mole fraction of the mixed gas throughout the desorption process. In the real-time correction algorithm, this level introduces the Extended Langmuir multi-component adsorption model. By combining individual component adsorption constants, the field equilibrium pressure, and the sensor-measured component mole fractions, the model dynamically calculates the adsorption capacity of different gas components within the coal matrix, thereby mitigating estimation errors induced by multi-component competitive adsorption.

The four-component tier encompasses components such as CH_4 , CO_2 , N_2 , and C_{2+} (e.g., Mine 1 in Anhui Province and Mine 2 in Henan Province in Table 2). The presence of heavy hydrocarbons alters the multi-component diffusion characteristics within the coal seam gas system; however, the traditional single-component square-root linear regression method often fails to accurately characterize lost gas patterns because it neglects differences in molecular diffusion rates. To address this, field operations can configure a micro-gas chromatography desorption analysis device equipped with an automatic sampling module at the wellhead to perform periodic, high-frequency component analysis. Beginning from the exposure of the coal core, the system continuously monitors the initial rapid desorption phase to construct a four-component dynamic evolution curve. To address lost gas compensation, this framework incorporates a numerical inversion method based on the Maxwell–Stefan multi-component diffusion model. By integrating early real-time desorption concentration and rate data, the system utilizes the Levenberg–Marquardt non-linear optimization algorithm to iteratively fit the diffusion parameters of each component, which subsequently estimates the initial component concentrations and characteristic diffusion parameters of the coal core, thereby enhancing the reliability of lost gas compensation in heavy hydrocarbon environments.

The full-component tier expands the analytical scope to include trace gases like H_2 , He, and Ar, as well as stable isotopes, primarily to establish scientific research baselines, trace complex geological hazards, and provide comprehensive early warnings for deep dynamic disasters. During the field sampling phase, high-pressure dual-valve sampling cylinders combined with vacuum gas collection methods enable the hermetic collection of gas samples from anomalous gas emission zones or structural belts. Upon delivering the samples to a surface laboratory, scientists employ a gas chromatography–mass spectrometer (GC–MS) to conduct full-component analysis. The system achieves low-concentration gas separation using a high-performance capillary chromatography column and accomplishes multi-component detection via a quadrupole mass analyzer, successfully fulfilling the requirements for trace gas identification. In hazard tracing and engineering analysis, investigators can leverage characteristic parameters, such as helium isotope ratios and carbon isotopes, to facilitate the identification of deep gas source origins and fluid migration features, thereby analyzing fracture development levels and fault connectivity characteristics. Furthermore, the high-precision full-component data from the GC–MS serves as a vital calibration baseline for field micro-gas chromatographs and optical sensors, establishing a joint laboratory-field correction mechanism that advances the stability and reliability of full-component measurement results.

In practical application, a “four-in-one” stepwise strategy should be adopted: broad-area screening using the single-component model; switching to the three-component correction upon encountering CO_2/N_2 anomalies; implementing four-component online monitoring for deep, high-heavy hydrocarbon zones; and initiating full-component source tracing for unexplained anomalies. This system aims to achieve a transition in coal gas measurement from “black-box total volume measurement” to “transparent component-based quantification,” thereby maximizing control over measurement errors.

7. Conclusions

Through a systematic investigation of gas component characteristics in typical Chinese mining areas and an analysis of multi-component competitive adsorption mechanisms, this study reveals the limitations of traditional gas content measurement systems under complex geological conditions. The results demonstrate that coalbed gas in China is not a simple, single-methane system, but rather a multi-component mixed gas system with significant heterogeneity. Specifically, CO_2 , N_2 , and certain heavy hydrocarbon compo-

nents account for a high proportion in deep coal seams, tectonically deformed coal zones, and areas with strong tectonic disturbance. Their competitive adsorption and differential desorption behaviors significantly alter the occurrence state and migration characteristics of coalbed gas. Comparative analysis of data from typical mining areas further indicates that different gas components exhibit distinct differences in adsorption constants, molecular kinetic diameters, and diffusion rates. However, current gas content measurement standards generally rely on a single-component methane assumption. This assumption fails to accurately reflect true desorption laws under multi-component conditions, thereby generating systematic deviations in lost gas compensation, residual gas calculation, and gas pressure inversion, which ultimately compromise the reliability of outburst danger evaluations. To address these issues, this study proposes a multi-component gas content measurement framework based on hierarchical measurement and real-time correction, which accounts for varying coal seam geological conditions and engineering application needs. Depending on the complexity of the gas components, the framework categorizes the measurement process into four hierarchical levels: single-component, three-component, four-component, and full-component. By incorporating the real gas equation of state, multi-component competitive adsorption models, and multi-component diffusion inversion methods, this framework achieves a dynamic balance between measurement accuracy and engineering costs. The proposed system reduces measurement deviations caused by component differences in traditional methods and improves the applicability and reliability of gas parameter measurements in complex coal seams, offering a new technical perspective for predicting outburst hazards in deep coal mines and evaluating coalbed methane resources.

Nevertheless, this multi-component measurement framework relies on sensor precision, data acquisition frequency, and the stability of field operating conditions, and it currently lacks validation from large-scale, long-term industrial applications. Therefore, future research must further investigate the universality of model parameters under complex geological conditions, the long-term stability of field equipment, and dynamic correction mechanisms under multi-scale coupling conditions. Future studies should focus on investigating multi-component gas occurrence laws and competitive adsorption mechanisms across different coal ranks, burial depths, and tectonic conditions to establish a regional parameter database. Researchers should also advance underground in situ real-time monitoring technology by integrating micro-gas chromatography, optical sensing, and intelligent desorption equipment. Finally, long-term field tests must validate the engineering applicability of the different measurement levels to provide data support and a theoretical basis for future revisions of national standards and industry regulations. Overall, integrating multi-component coupling effects and dynamic correction mechanisms into the gas parameter measurement system represents a crucial advancement for enhancing both the precise prevention and control of disasters in deep Chinese coal mines and the efficient development of CBM.

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