Desorption Effects and Laws of Multiscale Gas-Bearing Coal with Different Degrees of Metamorphism

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ABSTRACT: Understanding gas desorption effects and laws of coal mass under different conditions is essential for the effective exploration of gas emission in underground coal mines, prediction and prevention of coal and gas outburst, accurate detection of gas [coal methane (CBM)] content in coal seams, and prediction of CBM productivity. Using a self-developed test platform, we simulated gas adsorption and desorption and performed physical simulation tests. Based on these tests, we investigated the differences in the total amount of gas desorbed, desorption rate, and initial amount of gas desorbed by long-flame coal, coking coal, meager-lean coal, and anthracite on different scales under different gas pressures. Two methods are used for compensating gas loss, namely, the \( \sqrt{t} \) method and the power function method, as stipulated in the current Standards for Determination of Gas Content in Coal Seams in China. By combining these two methods, we analyzed the applicability of these two compensation methods in coal on different scales with varying degrees of metamorphism under gas pressures. The results demonstrated that (1) under the same gas adsorption pressure, the cumulative total amount of gas desorbed per unit mass within 90 min for the four kinds of coal samples increases with the degree of metamorphism. Changes in the cumulative amount of gas desorbed per unit mass and the desorption rate with the degree of metamorphism vary with stages. Notably, a higher adsorption pressure leads to a more obvious stage change. (2) Under the same gas adsorption pressure, the cumulative total amount of gas desorbed per unit mass and the desorption rate of coal with the same degree of metamorphism are inversely proportional to the size of the coal sample. This indicates significant scale effects. The larger the degree of metamorphism and gas adsorption pressure, the more significant are the scale effects of gas desorption. (3) For coal with the same degree of metamorphism, the higher gas adsorption pressure leads to a larger cumulative total amount of gas desorbed and a higher desorption rate throughout the desorption process and a larger proportion of the cumulative amount of gas desorbed in the initial stage. The smaller the size of the coal sample, the more obvious the pressure effects of gas desorption are. (4) For coal samples with the same degree of metamorphism, when the gas content in coal seams is kept constant, the larger the size of the coal sample, the smaller the actual gas loss is. Moreover, a higher gas content in coal seams results in a greater gas loss and a larger calculation error for gas loss. Compared with the \( \sqrt{t} \) method, the power function method reveals a smaller deviation between the calculated gas loss and the actual gas loss, which is found to be more accurate. A larger size coal sample results in higher accuracy in the calculated gas loss.

INTRODUCTION

Gas coalbed methane (CBM) in coal seams is a clean form of energy. However, it is also associated with deleterious effects in coal mining. The research on gas desorption laws of coal mass and their influencing factors is a hotspot in the field of prevention and control of gas disasters and exploration and production of CBM in coal mines. This is of great practical significance in exploring gas emission in underground mines, predicting and preventing coal and gas outbursts, improving the evaluation accuracy of gas content in coal seams, and predicting CBM productivity.1–4

Coal is a type of porous solid medium, with complex characteristics and a complex surrounding environment. Different factors are potentially linked to the large difference in the characteristics of gas desorption from coal mass. Currently, studies on desorption laws of gas-bearing coal and their influencing factors have advanced. These studies mainly focus on the impact and laws of the degree of metamorphism, gas pressure, failure type of coal mass, size of coal samples, pore structure, and moisture on desorption effects of gas-bearing coal. Yang,5 Nie,6 Han,7 Feng,8 Qin,9 Liu,10 and Chen11 conducted gas desorption tests on different scales of granular coal samples. The results revealed that the total

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amount of gas desorbed per unit mass and the gas desorption rate of coal at a given time decrease with an increase in the particle size of coal and remain unchanged after the coal particle size attains the limit. Ma and Zhang performed an adsorption—desorption experiment on 60–80 mesh granular coal and conducted the desorption process in four stages. Elsewhere, Ge, Li, and Yan explored differences in the desorption laws of bulk coal samples, columnar coal cores, and granular coal samples of anthracite. They found that the cumulative desorption rate, the cumulative amount of desorption, and desorption speed of the granular coal samples were larger compared to those of the columnar coal cores and bulk coal samples. Further, Cheng, Lin, Li, and Kang expounded mechanisms by which pore structures influence the rate and amount of gas desorption from the microperspectives of pore pattern and diameter. Wierzbicki reported that the cumulative amount and increment of the gas desorbed by granular coal increased with a temperature rise. The initial velocity of gas emission in the low-temperature environment was found to be much smaller than that in the normal-temperature environment. Also, Wang suggested that the loss of gas desorption is reduced by coring at a low temperature. With an increase in the degree of metamorphism of coal, the diffusion coefficient of methane first decreases and then gradually increases.

Through analysis of the change laws of the Langmuir effective diffusion coefficient with the coal rank and their influencing factors, Yan found that a rise in the coal rank increased the development degree of micropores and gas desorption capacity. Wang, Gao, and Lin concluded a higher adsorption pressure of coal mass is related to the stronger movement of methane molecules, more favorable for gas desorption, and accelerates gas diffusion. Additionally, the high pressure increases the diffusion coefficient and the cumulative amount of gas desorption and diffusion. In general, different degrees of metamorphism of coal are associated with different structures of coal mass, environmental factors, and gas desorption laws. Through several tests and theoretical analyses, relevant scholars have established multiple empirical formulas reflecting gas desorption laws, for example, those described by Wendt, Barrel, Wang, Airy, and Bott. Scholars have verified and analyzed the applicability of the above empirical formulas for gas desorption laws through tests and theoretical analyses. Notably, a new model of gas desorption and diffusion was established. For instance, Li revealed that the tectonic coal accords with Wendt’s empirical formula in the initial stage of gas desorption. Also, Qi found that empirical formulas described by Wendt and Wang Youan are more accurate in the low-temperature environment. Li utilized single-hole and double-hole models to establish a mode of dynamic gas diffusion in loaded coal and calculated diffusion coefficients of the coal samples with different particle sizes. Elsewhere, Liu and Wang constructed a gas desorption model considering the multiple diffusion coefficients. Collectively, the research results offer critical insights in determining the gas content in coal seams, prediction of gas emission from underground mines, prevention of gas disasters in coal mines, and exploration and production of CBM. However, most scholars used granular coal samples characterized by different particle sizes after artificial crushing and screening of the original coal mass. This distorts the original characteristics of the original coal mass and fails to simulate characteristics of the pore and fracture structures in the original underground coal mass. Some scholars have performed tests with large-scale coal samples and selected those exhibiting a single degree of metamorphism, which are not representative.

In coal seams, the gas content is a vital parameter for predicting the amount of gas emission, estimation of gas resources, and prevention of gas disasters during coal mining. Currently, the direct method commonly used to measure the gas content in coal seams is directed underground. With the direct method, gas content in coal seams is measured in three parts, loss, measurable amount of desorption, and residual amount. The loss is calculated based on desorption laws, whereas the measurable amount of desorption and the residual amount are the true readings. Therefore, to establish the gas content in coal seams, the accuracy of the direct method is determined by the accuracy of loss calculation. Practically, the exposure time of the coal samples can be accurately evaluated. The desorption laws within the exposure time, that is, the accuracy of the desorption model, are crucial in measuring the error of loss. Based on the above reports, most desorption models integrate empirical formulas. Also, the correlation coefficients for fitting gas desorption models under different conditions are different. To improve the accuracy of the assessment of gas content in coal seams, industries and academia have extensively explored and reviewed models of loss calculation. In China, the national standard, Direct Method of Determining Coalbed Gas Content in the Mine (GB/T23250-2009), indicate that the \( \sqrt{i} \) method and the power function method are commonly applied to calculate gas loss. The standard also shows that with sampling methods, cuttings of granular coal are collected from fixed points. A fixed-point sampler is used to drill holes into coal seams or collect columnar coal cores with a coal core sampler. Previous studies expressed both the \( \sqrt{i} \) method and the power function method using empirical formulas. Their applicability in the gas desorption of coal drill cuttings (granular) and coal cores (columnar) samples under different degrees of metamorphism and gas pressures differ, which warrants further exploration.

Based on the current understanding, there is no consensus on which desorption law should be applied when calculating loss. Also, no systematic study has explored gas desorption laws and differences between large-scale coal samples through a reflection of the characteristics of the original coal mass and small-scale granular coal samples after artificial crushing and screening. Moreover, the applicability of two generally used methods (\( \sqrt{i} \) method and power function method) for gas loss calculation in the coal samples with different degrees of metamorphism, gas pressures, and scales has not been systematically investigated. In consequence, the methods that compensate for the gas content are more erroneous and do not guarantee the accuracy of determining the gas content.

On this basis, four types of coal samples with different degrees of metamorphism from different mining areas were used in tests. Desorption tests under different gas pressures during adsorption were conducted through the drilling of different sizes of columnar coal samples and crushing and screening into different particle sizes of granular coal samples. We aimed to explore the gas desorption laws of columnar coal samples by approximately reflecting the original coal mass and their differences in the desorption laws of granular coal samples. This study explored and analyzed the applicability of the two methods for compensating gas loss, the \( \sqrt{i} \) method and the power function method, in coal with different scales,
gas pressures, and degrees of metamorphism. We expect that the findings will reveal desorption effects and laws of multiscale gas-bearing coal with different degrees of metamorphism and provide a basis for the selection of the optimal sampling method for establishing the gas content in coal seams and the best method for compensating the loss.

### SAMPLE PREPARATION AND METHODS IN TESTS

**Sample Collection and Preparation for Tests.** The four types of coal samples with different degrees of metamorphism were collected for testing. They included anthracite from Jiaozuo Mining Area (Henan Province), meager-lean coal from Qinshui Coalfield (Shanxi Province), coking coal from Anyang Mining Area (Henan Province), and long-flame coal from Yujialiang Mining Area (Shaanxi Province), China. The collected samples were sealed with plastic films and transported to the laboratory. The columnar coal samples with two dimensions of 50 mm * 100 mm (diameter: 50 mm, height: 100 mm) and 37.5 mm * 75 mm (diameter: 37.5 mm, height: 75 mm) were drilled using a core-drilling machine (Figure 1a).

**Figure 1.** Coal samples used in tests.

The remaining coal samples were crushed and screened into granular coal samples with particle sizes of 1−3 mm and 0.5−1 mm (Figure 1b). We prepared 16 test samples. Table 1 displays the basic parameters of the four types of coal with different degrees of metamorphism.

| coal number | degrees of metamorphism | coal structure          | $M_{ad}$ | $A_{ad}$ | $V_{ad}$ |
|-------------|-------------------------|-------------------------|---------|---------|---------|
| WYM         | anthracite              | native structure        | 3.06    | 15.18   | 9.44    |
| PSM         | meager-lean coal        | native structure        | 0.45    | 8.58    | 17.97   |
| JM          | coking                  | native structure        | 0.67    | 10.81   | 21.37   |
| CYM         | long-flame coal         | native structure        | 6.41    | 1.90    | 38.16   |

**Table 1. Basic Parameters of the Coal Samples in Tests**

**Test Devices and Methods.** Following the requirements of test conditions, a set of adsorption and desorption test system (Figure 2) with temperature control functions was designed and installed independently and met the test requirements of columnar and granular coal samples simultaneously. The whole system mainly comprised four parts, a high-pressure gas-filling unit (1, 2, and 4), a gas adsorption−desorption unit (8 and 10), a constant-temperature regulating unit (9), and a vacuum degassing unit (7). Five major processes constituted this test: (i) dehydration of the coal samples, (ii) calibration of the dead-space volume, (iii) canning and degassing of the coal samples, (iv) gas (methane) adsorption of the coal samples under a high pressure, and (v) gas desorption under normal pressure. The pressures for adsorption equilibrium of the coal samples in the test were set at an equal gradient in the range of 0.5−3 MPa as follows: 0.5, 1, 1.5, 2, 2.5, and 3 MPa. The time of adsorption equilibrium of the columnar coal samples was longer than 4 d, whereas that of the granular coal samples was longer than 2 d. The temperature set in the test was 30 °C, and the coal samples were desorbed for 3 h.

**TEST RESULTS AND DISCUSSION**

**Coal Rank Effects of Gas Desorption.** The columnar coal samples with 50 mm * 100 mm dimensions and granular coal samples with a particle size of 1−3 mm of anthracite, meager-lean coal, coking coal, and long-flame coal with different degrees of metamorphism were selected. Based on the data of the desorption test recorded under the adsorption pressures of 1, 2, and 3 MPa within 90 min, we did a comparison and analysis of the change characteristics of the cumulative total amount of gas desorbed per unit mass and gas desorption rate with the degree of metamorphism. The effects of coal ranks and laws of gas desorption from coal mass were further revealed (Figures 3 and 4).

Based on the analysis of Figures 3 and 4, the coal with different degrees of metamorphism at the same scale exhibits the following characteristics in terms of the cumulative total amount of gas desorbed and the desorption rate.

1. Under the same adsorption pressure, according to the cumulative total amount of gas desorbed per unit mass within 90 min, anthracite, meager-lean coal, coking coal, and long-flame coal are ranked in descending order. That is, the cumulative total amount of gas desorbed increases with the degree of metamorphism. For instance, at an adsorption pressure of 3 MPa, the cumulative total amount of gas desorbed by the granular coal samples of anthracite, meager-lean coal, and coking coal within 90 min is 2.06, 1.61, and 1.45 times that of the granular coal samples of long-flame coal, respectively. This law was mainly determined by the adsorption capacity of coal with different degrees of metamorphism such that the greater the adsorption capacity, the larger the total amount of gas desorbed.

2. Under the same adsorption pressure, except for long-flame coal with a low degree of metamorphism, the other three types of coal with medium and high degrees of metamorphism show the following laws always. Particularly, anthracite, meager-lean coal, and coking coal are ranked in a descending order. This is according to the changes of the cumulative total amount of gas desorbed and the desorption rate with an increase in the degree of metamorphism in the entire desorption process. The desorption rates of coal with different degrees of metamorphism are largely different in the initial desorption stage. Later, the difference in desorption rates becomes increasingly small and the desorption rate tends to be approximate.

3. Compared to the other three types of coal with medium and high degrees of metamorphism, the cumulative amount of gas desorbed and the desorption rate of long-
flame coal are larger in the initial stages. It takes less time to attain the maximum desorption. At a pressure of 3 MPa, the amount of gas desorbed by the granular coal samples of long-flame coal with a particle size of 1−3 mm in the first 3 and 5 min accounts for 67.0 and 68.5% of the total amount of gas desorbed within 90 min, respectively. Notably, under the same conditions, the amount of gas desorbed by anthracite in the first 3 and 5 min is 28.9 and 35.4% of the total amount of gas desorbed within 90 min, respectively. Such characteristics mainly are influenced by the development and good connectivity of pores and fractures in long-flame coal.

(4) Considering the four types of coal with different degrees of metamorphism, the changes in their cumulative amount of gas desorbed and desorption rates with the degree of metamorphism in the whole desorption process are segmented. In the initial desorption stage, the cumulative amount of gas desorbed and the desorption rate of long-flame coal are large. They are larger compared to those of coking coal, meager-lean coal, and anthracite. Following an increase in the desorption time, the cumulative amount of desorption and desorption rates of long-flame coal is smaller than those of coal with medium and high degrees of metamorphism. A higher adsorption pressure implies that the phenomenon is more obvious. Figures 3a and 4a demonstrate that, under an adsorption pressure of 1 MPa, anthracite, long-flame coal, meager-lean coal, and coking coal are ranked in a descending order based on the cumulative amount of gas desorbed and desorption rate of the granular and columnar coal samples within 5 min of desorption time. Within 5−10 min, anthracite, meager-lean coal, long-flame coal, and coking coal are ranked in a descending order based on the cumulative amount of gas desorbed and desorption rate. An ascending order is found in long-flame coal, coking coal, meager-lean coal, and anthracite according to the cumulative amount of gas desorbed and desorption rate in more than 10 min. Figures 3c and 4b illustrate that,
under an adsorption pressure of 3 MPa, long-flame coal, anthracite, meager-lean coal, and coking coal are ranked in a descending order based on the cumulative amount of gas desorbed and the desorption rate within 10 min. Within 10–20 min, the cumulative amount of gas desorbed and the desorption rate of anthracite are the largest, followed by long-flame coal and meager-lean coal. However, the smallest cumulative amount of gas desorbed and desorption rate are found in coking coal. Within 20–30 min, a descending order is found in anthracite, meager-lean coal, long-flame coal, and coking coal, whereas an ascending order is presented in long-flame coal, coking coal, meager-lean coal, and anthracite at a desorption time longer than 30 min. Such phenomena are mainly established by the adsorption capacity and development degree of pores and fractures in coal with different degrees of metamorphism. The development and good connectivity of pores and fractures in long-flame coal results are because the initial desorption capacity increases, whereas the desorption accelerates. However, the gas adsorption capacity eventually demonstrates that the total amount of desorption is small.

Scale Effects of Gas Desorption. The columnar coal samples with the dimensions of 37.5 mm * 75 mm and 50 mm * 100 mm and granular coal samples with the particle sizes of 0.5–1 and 1–3 mm of anthracite, meager-lean coal, and long-flame coal with different degrees of metamorphism were selected. This was followed by a comparison and analysis of the change characteristics of the cumulative amount of gas desorbed per unit mass and the gas desorption rate with the scale based on the desorption test data under adsorption pressures of 1 and 3 MPa (Figures 5 and 6). Then, scale effects and laws of gas desorption from coal mass were revealed.

Based on the analysis of Figures 5 and 6, the columnar and granular coal samples with different sizes exhibit the following characteristics of the cumulative amount of gas desorbed and desorption rates.

(1) Under the same pressure of adsorption equilibrium, coal samples with the same degree of metamorphism, the cumulative amount of gas desorbed per unit mass, and the desorption rate have an inverse relationship with the sizes of the samples in the whole desorption process, and the maximum desorption is attained. That is, the smaller size implies a larger cumulative amount of desorption and desorption rates, demonstrating noticeable effects.

Figure 4. Comparison of the gas desorption rates of coal with different degrees of metamorphism.
on the particle size. Among all the coal samples, the granular coal samples with a particle size of 0.5−1 mm exhibit the largest cumulative amount of gas desorbed and desorption rate, followed by the granular coal samples with a particle size of 1−3 mm. The columnar coal samples with the dimensions of 50 mm * 100 mm show the smallest cumulative amount of gas desorbed and desorption rate. Figures 5f and 6d demonstrate that, under an adsorption pressure of 3 MPa, the cumulative amounts of gas desorbed by the granular coal samples with a particle size of 0.5−1 mm for 40 min are 1.37, 1.68, and 1.87 times that of the granular coal samples with the particle size of 1−3 mm and columnar coal samples with dimensions of 37.5 mm * 75 mm and 50 mm * 100 mm. Furthermore, its desorption rate is 1.27, 1.56, and 1.74 times that of the granular coal samples with the particle size of 1−3 mm and columnar coal samples with dimensions of 37.5 mm * 75 mm and 50 mm * 100 mm. The main reason for such particle size effects is that the fractures in the granular coal samples are more developed compared to the columnar coal samples due to artificial crushing. Also, the small particle size of granular coal makes the paths for desorbing gas adsorbed in the matrix become shorter and smoother.

(2) Under the same adsorption pressure, an increase in the degree of metamorphism shows more noticeable particle size effects on the cumulative amount of gas desorbed and desorption rate. Figure 5a,c,e illustrate that, under an adsorption pressure of 1 MPa and 20 min desorption time, the differences between the cumulative amount of gas desorbed by anthracite with the particle size of 0.5−1 mm and the granular coal samples with the particle size of 1−3 mm and columnar coal samples with the dimensions of 37.5 mm * 75 mm and 50 mm * 100 mm are 0.39, 0.79, and 1.07 cm³/g. Under an adsorption pressure of 3 MPa, the differences are 1.87, 2.61, and 2.89 cm³/g, higher than those of particle size effects for gas desorption under an adsorption pressure of 1 MPa. Notably, meager-lean coal and anthracite show the same laws.

Pressure Effects of Gas Desorption. By selecting anthracite and long-flame coal with the particle sizes of 0.5−1 mm and the dimensions of 50 mm * 100 mm, we obtained data of the desorption test under the adsorption pressures of 0.5, 1, 1.5, 2, 2.5, and 3 MPa (Figures 7 and 8). The change characteristics of the cumulative amount of gas desorbed per unit mass and gas desorption rate with the adsorption pressure were compared and analyzed. Eventually, we revealed the pressure effects and laws of gas desorption from coal mass. Based on the analysis of Figures 7 and 8, the coal samples exhibit the following characteristics in the cumulative amount of gas desorption with increasing adsorption pressure.
of gas desorbed and the desorption rate under different adsorption pressures.

1. Higher the adsorption pressure in the whole desorption process implies that the cumulative amount of gas desorbed and the desorption rate are larger for coal with the same degree of metamorphism. To explain this, a higher adsorption pressure is related to a larger amount of adsorption of coal. When the equilibrium is damaged, a higher adsorption pressure results in a more violent movement of methane molecules, which becomes more conducive to gas desorption and accelerates gas desorption.

2. Higher adsorption pressure causes a larger desorption rate and the cumulative amount of desorption in the initial desorption stage for coal with the same degree of metamorphism. Figures 7b and 8b demonstrate that, under 5 min of desorption, the cumulative amounts of gas desorbed per unit mass of the granular samples of anthracite with the particle size of 0.5−1 mm with an adsorption pressures of 3 MPa are 1.13, 1.22, 1.41, 1.62, and 2.33 times that of those under the pressures of 2.5, 2, 1.5, 1, and 0.5 MPa, respectively. Moreover, the desorption rate under the adsorption pressure of 3 MPa is 1.13, 1.21, 1.41, 1.63, and 2.33 times that of those under the pressures of 2.5, 2, 1.5, 1, and 0.5 MPa, respectively.

3. For coal samples with the same degree of metamorphism, smaller size of coal samples depicts more obvious pressure effects of gas desorption. That is, under the same difference of pressures for gas adsorption, the smaller size of coal samples is related to larger corresponding differences in the cumulative amount of gas desorbed and the desorption rate. Figure 7a,b demonstrates that, under the adsorption pressure of 3 MPa, the cumulative amount of gas desorbed per unit mass of the granular coal samples of anthracite with the particle size of 0.5−1 mm shows differences of 0.65, 1.19, 1.76, 2.24, and 3.09 cm³/g with those under 2.5, 2, 1.5, 1, and 0.5 MPa pressures in 10 min desorption time, respectively. Within 10 min, the cumulative amount of gas desorbed per unit mass of the columnar coal samples of anthracite with the dimensions of 50 mm × 100 mm under an adsorption pressure of 3 MPa shows differences of 0.40, 0.62, 0.90, 1.28, and 1.86 cm³/g with those under 2.5, 2, 1.5, 1, and 0.5 MPa pressures, respectively. Such differences are smaller than those of the granular coal samples with a particle size of 0.5−1 mm. Figure 8a,b illustrates the same characteristics in the desorption rate.

Discussion on Methods for Compensating the Gas Loss. The accuracy of methods for loss calculation determines the accuracy of measurement of the gas content in under-
ground coal seams. In China, the √\(t\) method and power function methods complying with the national standards are applied to calculate the gas loss in the early stages of measurement. According to the above desorption test data of gas-bearing coal, we compared and analyzed the errors of the two methods under different scales, degrees of metamorphism, and gas pressures. The applicability of the two methods was also reviewed, which we believe can significantly guide and improve the accuracy of establishing the gas content in coal seams.

The √\(t\) method is based on the linear relationship between the cumulative amount \(V\) of gas desorbed and the square root \(\sqrt{t + t_0}\) of the total desorption time within a certain period after exposure of the coal samples, which is expressed as follows:

\[
V = K\sqrt{t + t_0} - V_s' \tag{1}
\]

where, \(t\), \(t_0\), and \(V\) represent the gas desorption time (min), exposure time (min) of the coal samples, and the cumulative amount (cm\(^3\)) of desorption within \(t\), respectively, and \(V_s'\) and \(K\) denote the amount (cm\(^3\)) of gas desorbed within \(t_0\) and undetermined constant, respectively.

The power function method is to transmit the measured data \((t, V_t)\) into the data of the desorption rate \((q_t, q_0)\) and then calculate \(q_0\) and \(n\) by fitting through the formula:

\[
q_t = q_0(1 + t)^{-n} \tag{2}
\]

where, \(q_t\), \(q_0\), and \(t\) denote the gas desorption rate at \(t\), gas desorption rate when \(t = 0\), and gas desorption time, respectively, and \(n\) represents the attenuation coefficient of the gas desorption rate and \(0 < n < 1\). The loss is calculated by the formula:

\[
V_s = q_0 \frac{(1 + T_0)^{1-n} - 1}{1-n} = \frac{V_0}{1-n} - V_0 \tag{3}
\]

where, \(V_s\) and \(T_0\) indicate the gas loss in the coal samples and exposure time of the coal samples, respectively.

Furthermore, we obtained the desorption data of anthracite, meager-lean coal, coking coal, and long-flame coal with the dimensions of 50 mm * 100 mm and the particle size of 0.5–1 mm under the adsorption pressures of 0.5, 1, and 3 MPa. Assuming that the exposure time is 2 min, the applicability and accuracy of the two methods in calculating gas loss were compared and analyzed (results are shown in Table 2).
Through analysis of the data in Table 2, the following understandings can be reached.

1. Under the same adsorption pressure, the actual loss of large-scale columnar coal samples is smaller than that of small-scale granular coal samples for the coal samples with the same degree of metamorphism. Besides, a higher pressure for gas adsorption, that is, a higher gas content in coal seams denotes a greater gas loss within the same exposure time for coal samples with the same degree of metamorphism and scale.

2. As shown in Figure 9, compared to the √t method, the deviation between the gas loss calculated by fitting according to the power function method and the actual gas loss is smaller, demonstrating a higher accuracy. Meanwhile, gas desorption data in the initial stage should be selected when calculating the gas loss using the √t method. A longer time span of the selected data would mean a larger error. Therefore, the gas desorption data in the first 5 min were selected in this calculation, while those in the first 20 min were selected for calculation using the power function method.

3. The accuracy of gas loss calculated by both the √t method and the power function method shows noticeable effects on the particle size such that a larger size of the coal sample implies a higher accuracy of gas loss calculation. For anthracite under an adsorption pressure of 0.5 MPa, the deviations of the gas loss of the columnar and granular coal samples calculated by the √t method are 0.43 and 0.58 cm$^3$/g, while those calculated using the power function method are 0.19 and 0.24 cm$^3$/g as compared to the actual loss.

4. A higher adsorption pressure, that is, a higher gas content in coal seams, denotes a larger error of the calculated gas loss. For the meager-lean coal with the particle size of 0.5−1 mm, the deviations between the gas loss calculated with the √t method and the actual loss are 0.19, 0.27, and 0.58 cm$^3$/g under the adsorption pressures of 0.5, 1, and 3 MPa. Under the same conditions, the deviations between the gas loss calculated by the power function method and the actual loss are 0.12, 0.15, and 0.33 cm$^3$/g.

5. Compared to the other coal samples with medium and high degrees of metamorphism, the error of the gas loss of long-flame coal calculated via the √t method is larger, especially under a higher adsorption pressure. Similarly, by selecting the gas desorption data in the first 5 min for calculation, the correlation coefficient after fitting of the long-flame coal is smaller than those of the other coal
samples. At the same time, the deviation of gas loss under the high adsorption pressure is larger. Under an adsorption pressure of 3 MPa, the deviation of gas loss of the columnar coal samples with the dimensions of 50 mm * 100 mm from the actual loss is 1.86 cm³/g, whereas that of the granular coal samples with the particle size of 1 mm is 2.27 cm³/g. When gas loss of long-flame coal is calculated via the $\sqrt{t}$ method, gas desorption data within a shorter time span, for example, in the first 3 min, can be selected according to the actual situations, thereby improving the accuracy of gas loss calculation.

(6) Based on the WY columnar coal sample desorption data under 0.5 MPa adsorption pressure, the deviation of the gas loss of the two compensation methods at different exposure times was compared and analyzed, so as to explore the influence of the exposure time on the accuracy of the compensation method.

As shown in Figure 9, regardless of the power function method or the $\sqrt{t}$ method, the gas loss deviation increases with the increase of exposure time, that is, the longer the exposure time, the lower the accuracy of the loss compensation method is.

| Table 2. Gas Content Measurement Results of Loss Using the $\sqrt{t}$ Method and the Power Function Method |
|---|---|---|---|---|---|---|---|
| coal number | size (mm) | pressure (MPa) | $\sqrt{t}$ | $R_t^2$ | power function | $R_k^2$ | actual loss (cm³/g) | $\sqrt{t}$ | power function |
| WYM | 50*100 | 0.5 | 0.40 | 0.9940 | 0.64 | 0.9962 | 0.83 | 0.43 | 0.19 |
| | | 1 | 0.61 | 0.9969 | 0.91 | 0.9937 | 1.13 | 0.52 | 0.22 |
| | | 3 | 0.92 | 0.9953 | 1.57 | 0.9949 | 1.98 | 1.06 | 0.41 |
| | 0.5-1 | 0.5 | 0.61 | 0.9989 | 0.95 | 0.9947 | 1.19 | 0.58 | 0.24 |
| | | 1 | 0.89 | 0.9960 | 1.36 | 0.9935 | 1.69 | 0.80 | 0.33 |
| | | 3 | 1.96 | 0.9999 | 2.10 | 0.9958 | 2.60 | 0.64 | 0.50 |
| PSM | 50*100 | 0.5 | 0.34 | 0.9982 | 0.35 | 0.9983 | 0.43 | 0.09 | 0.08 |
| | | 1 | 0.50 | 0.9960 | 0.59 | 0.9955 | 0.71 | 0.21 | 0.12 |
| | | 3 | 0.85 | 0.9902 | 1.15 | 0.9964 | 1.42 | 0.57 | 0.27 |
| | 0.5-1 | 0.5 | 0.57 | 0.9982 | 0.64 | 0.9906 | 0.76 | 0.19 | 0.12 |
| | | 1 | 0.70 | 0.9931 | 0.82 | 0.9894 | 0.97 | 0.27 | 0.15 |
| | | 3 | 1.22 | 0.9960 | 1.47 | 0.9970 | 1.80 | 0.58 | 0.33 |
| JM | 50*100 | 0.5 | 0.30 | 0.9995 | 0.33 | 0.9968 | 0.41 | 0.11 | 0.08 |
| | | 1 | 0.48 | 0.9970 | 0.53 | 0.9929 | 0.65 | 0.17 | 0.12 |
| | | 3 | 0.82 | 0.9987 | 1.11 | 0.9972 | 1.37 | 0.55 | 0.26 |
| | 0.5-1 | 0.5 | 0.48 | 0.9960 | 0.56 | 0.9964 | 0.68 | 0.20 | 0.12 |
| | | 1 | 0.60 | 0.9970 | 0.73 | 0.9929 | 0.88 | 0.28 | 0.15 |
| | | 3 | 1.00 | 0.9991 | 1.42 | 0.9959 | 1.77 | 0.77 | 0.35 |
| CYM | 50*100 | 0.5 | 0.20 | 0.9900 | 0.43 | 0.9915 | 0.54 | 0.34 | 0.11 |
| | | 1 | 0.22 | 0.9853 | 0.68 | 0.9941 | 0.88 | 0.66 | 0.2 |
| | | 3 | 0.65 | 0.9859 | 1.96 | 0.9919 | 2.51 | 1.86 | 0.55 |
| | 0.5-1 | 0.5 | 0.22 | 0.9687 | 0.51 | 0.9897 | 0.65 | 0.43 | 0.14 |
| | | 1 | 0.27 | 0.9755 | 0.90 | 0.9915 | 1.13 | 0.86 | 0.23 |
| | | 3 | 0.73 | 0.9880 | 2.28 | 0.9933 | 3.00 | 2.27 | 0.72 |

Figure 9. Comparison of the deviation of loss for different exposure times
and even anthracite. Following desorption, the cumulative amount of gas desorbed and the desorption rate of long-flame coal are smaller than those of anthracite, meager-lean coal, and coking coal. A higher adsorption pressure implies more noticeable segmentation.

(2) The columnar and granular coal samples exhibit noticeable differences in the characteristics of gas desorption. For coal with the same degree of metamorphism, the cumulative amount of gas desorbed per unit mass and the desorption rate of the columnar coal samples are significantly smaller than those of the granular coal samples in the whole desorption process before attaining maximum desorption under the same adsorption pressure. The smaller size is related to a larger desorption rate and the cumulative amount of gas desorbed, demonstrating noticeable scale effects. Of note, higher degrees of metamorphism and adsorption pressure imply that the scale effects of gas desorption become more significant.

(3) The adsorption pressure plays a decisive role in the desorption rate and cumulative amount of desorption before the maximum adsorption is achieved. For coal with the same degree of metamorphism, a higher adsorption pressure means that the cumulative amount of gas desorbed and the desorption rate become larger in the whole desorption process. Similarly, a larger proportion of the cumulative amount of gas is desorbed in the initial stage. When the coal sample is smaller, more pressure effects of gas desorption are realized. Briefly, under the same difference in adsorption pressures, a smaller coal sample is associated with larger differences in the corresponding cumulative amount of gas desorbed and desorption rate.

(4) The gas content in underground coal seams was established through the collection of columnar coal cores using the coal core sampler. The loss is smaller within the same exposure time. The loss calculation using the power function method is more accurate compared to the \( f^2 \) method. For coal samples with the same degree of metamorphism, when the gas content in coal seams is the same, the actual loss of large-scale columnar coal samples is smaller than that of small-scale granular coal samples. A higher gas content in coal seams implies a greater gas loss within the same exposure time and a larger error of gas loss calculation. In comparison to the \( f^2 \) method, the gas loss calculated by the power function method depicts a smaller deviation with the actual gas loss but with a higher accuracy. In addition, the accuracy of the two calculation methods shows obvious effects of a particle size such that the larger scale of the coal samples denotes a higher accuracy of the gas loss calculation.

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**Notes**

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