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Prediction of coal seam gas content based on the correlation between gas basic parameters and coal quality indexes

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The measurement of gas content in coal seam by means of indirect method involves heavy workload, long period, high cost and complicated operation and a proneness of negative values in the process of measuring gas absorption constant. To address these problems, the gas basic parameters and coal quality indexes of 90 coal samples from 90 coal mines in 13 provinces of China are determined experimentally in this paper. The intrinsic relationship between gas adsorption constant a and atmospheric adsorption capacity Q_0-initial velocity index of gas emission Δp, gas adsorption constant b and volatile V_{daf} - apparent density ARD is analyzed, and a prediction model of coal seam gas content based on gas basic parameters and coal quality index is established. The results show that the effect of Q_0-Δp correlation on a is mainly caused by the change of specific surface area and gas pressure of coal, while the effect of V_{daf}-ARD correlation on b is mainly caused by the change of pore volume of coal. By comparing the predicated value from the prediction model of coal seam gas content with the measured value, it is found that the average absolute error rate of predicted value is 8.15%. This method is proven to be effective and feasible in routine gas content predictions, and can provide a reference for coal seam gas content prediction in China.

KEYWORDS

coal seam gas content, gas basic parameters, coal quality index, prediction model, absolute error

1 Introduction

Coal seam gas content has an immediate impact on the amount of coal seam gas and the amount of mine gas emission, which is of great significance for the appropriate design of mine ventilation, gas drainage, outburst risk assessment and so on (Wang et al., 2018; Zhou et al., 2022a; Ma et al., 2022). The determination method of gas content in coal seam includes direct method and indirect method (Zhou, 2014; Lei et al., 2018; Cheng et al., 2019). The direct method is used to determine the desorption gas quantity and atmospheric gas quantity in the underground field and laboratory, and then calculate the gas loss in the sampling process, and the sum of the three parts is the gas content in the coal seam. On the basis of the gas adsorption constant and coal quality index measured in the laboratory, as well as the coal seam gas pressure measured in the field, the indirect method is used to calculate the adsorption gas quantity and free gas quantity of coal through Langmuir equation, and the sum of the two parts is the gas content of coal seam. Compared with the direct method, the parameters measured by the indirect method are all measured values, including the gas pressure in the coal seam, and as there are fewer influencing factors in the process of measurement, the measurement error is small, and the measured data has higher credibility. The values measured by direct method are often lower than the actual values, whereas the values measured by indirect method in many mines are often closer to the actual values (Li et al., 2020; Wang et al., 2022). However, the indirect method has its deficiencies-the measurement of gas adsorption constant needs to be done in laboratory and the measurement of coal-seam gas pressure needs to be done in the pit. These involve heavy workload, long period, high cost, complex operation and high technical requirements. The measurement of coal-seam gas pressure is quite difficult, especially in the gently inclined coal seam or the coal seam with poor compactness of surrounding rock. For the coal samples with very low degree of metamorphism or coal samples with a large amount of coal gangue, the gas adsorption constant is often negative, which is not consistent with the theory, making it impossible to determine the gas content in coal seam using indirect method.

As there are various factors affecting coal seam gas content, and gas occurrence features complexity, non-linearity, dynamic and random uncertainty, it is difficult to accurately determine and predict coal seam gas content (Scott, 2002; Xiang, 2017; Long et al., 2018; Wang et al., 2019; Malinnikova et al., 2020; Si et al., 2021a; Banerjee and Chatterjee, 2021; Deng, 2021; Xiao et al., 2022). In recent years, a significant body of researchers have devoted to the prediction of gas content in coal seams and achieved fruitful results. Li (2014) and Wang (2015) established a mathematical model for predicting coal seam gas content based on drilling cuttings gas desorption index method. Gao et al. (2015) established a multivariate linear regression model for predicting coal seam gas content by using partial least square multiple linear regression. Hao and Sun (2015), Xu et al. (2019) and Zhou et al. (2016) used grey theory to construct the prediction method of coal seam gas content. Lin et al. (2020) proposed a gas content prediction model (PSO-BP model) based on particle swarm optimization (PSO) optimization error back propagation (BP) neural network. Zhao et al. (2022) established a gas content prediction model (ACSOA-BP) based on adaptive chaotic seagull algorithm optimized BP neural network. Wei and Pei (2019) established a coal seam gas content prediction model based on PCA-AHPSO-SVR, and found that the average accuracy of the proposed PCA-AHPSO-SVR model is 5.51% and 9.32% higher than that of PCA-PSO-SVR and PSO-SVR model, respectively. In a study by Wang et al. (2016), a new method of coal seam gas content measurement based on the small gap of gas adsorption and desorption characteristics of coal seams in the same geologic unit was proposed. Li et al. (2019) used a support vector machine (SVM) network for sensitive parameters training based on genetic constraints to establish a set of prediction methods for the volume gas content. Zhou et al. (2022b) built a collaborative prediction model of gas emission quantity by feature selection and supervised machine learning algorithm to improve the scientific and accurate prediction of gas emission quantity in the mining face.

As can be seen from the above research, the existing prediction models of coal seam gas content are focused on the relationship between coal seam gas content and influencing factors such as coal seam depth, coal seam thickness, floor elevation, fault distance, coal seam dip angle and so on. However, the predication of coal seam gas content based on the correlation between gas basic parameters and coal quality indicators is rarely studied. Coal quality indexes include moisture M_{ad}, ash A_{ad}, volatile V_{daf}, initial gas release velocity Δp, firmness coefficient f, atmospheric adsorption capacity Q_0 and so on. They macroscopically reflect some essential characteristics related to coal and gas adsorption and desorption, among which Δp and f often used to predict regional outburst risk (Hu, 2020; Lei, 2022; Wang, 2022). These parameters are characterized by quick measurement in the laboratory, low cost and are simple operation. Therefore, a substitution in place of the gas adsorption constant needs to be identified based on the correlation between the gas basic parameters and the coal quality index, so as to provide a solution to the unavailability of the indirect method to determine the coal-seam gas content due to the negative values measured by gas adsorption constant for a small number of coal samples. This offers a new technology and method for the prediction and application of mine gas disaster prevention, coal and gas outburst prediction, coal seam gas drainage and so on.

2 Determination of gas basic parameters

2.1 Determination method of gas adsorption constant

The gas adsorption constant of coal characterizes the adsorption capacity of coal to methane, reflecting the maximum gas adsorption capacity and coal quality characteristics (Lei, 2017). The purpose of determining the gas adsorption constant in the laboratory is to calculate the gas content in coal seam, which is an indirect method to determine the gas content in coal seam. At present, the roadways in a vast

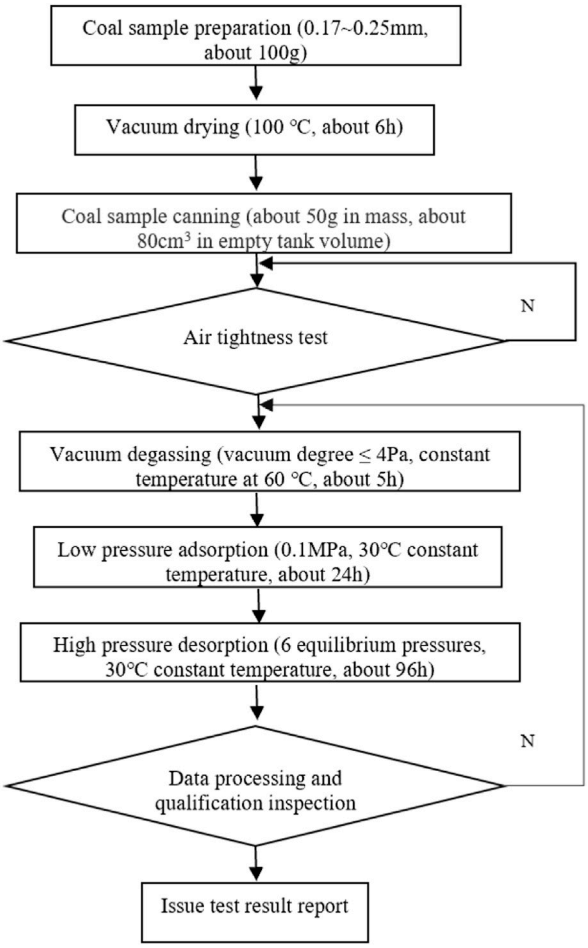

FIGURE 1
Measurement process of HCA-1 high pressure volume gas adsorption device.

majority of mines are located along the coal seam, so the indirect method is widely used to determine the gas content in coal seams (Zhao and Jia, 2019; Plaksin and Kozyreva, 2021). High pressure volumetric method is used to determine adsorption constant (7 gas adsorption capacities corresponding to 7 equilibrium pressures with approximate average distribution in the range of 0~5 MPa are measured), and the HCA-1 high pressure capacity method (Chen et al., 2012; Zhang et al., 2015; Zhou et al., 2019) is used to determine the experimental determination process of gas adsorption device as shown in Figure 1.

2.2 Coal sample collection and test

Ninety coal samples were collected from 90 coal mines in 13 provinces, including Guizhou, Jiangxi, Anhui, Xinjiang, Sichuan, Liaoning, Shaanxi, Henan, Shanxi, Jilin, Qinghai, Yunnan and Inner Mongolia. According to the national standards such as GB/T 482-2008 “Methods for Coal Seam Samples”, GB/T 474-2008 “Coal Sample Preparation Methods”, GB/T 477-2008 “Coal Sample Sieving Test Methods” and other national standards, about 5 kg powder mixed coal samples taken from freshly exposed coal seams, after being marked with the mine name and sampling location on the tightly sealed packages, were sent to the laboratory for numbering, registration, sampling, drying, crushing, sieving, etc., before they were prepared to be coal samples of different particle sizes for inspection.

2.3 Test results

According to the coal industry standards and national standards such as MT/T 752-1997 “Method for Determination of Methane Adsorption of Coal”, GB/T 212-2008 “Method for Industrial Analysis of Coal”, GB/T 217-2008 “Method for Determining the True Relative Density”, and GB/T 6949-2008 “Method for Determination of Apparent Relative Density of Coal”, 90 coal samples were measured in the laboratory using HCA-1 high pressure volumetric gas adsorption device, industrial analysis instrument, density meter and other instruments and equipment. More specifically, the coal quality indexes and gas basic parameters such as moisture M_{ad}, ash A_{ad}, volatile V_{daf}, true density TRD, apparent density ARD, porosity F, atmospheric adsorption capacity Q_0, gas adsorption constant a, b, initial velocity index of gas emission Δp and firmness coefficient of coal f were measured in the laboratory. The measured results of the 90 coal samples are shown in Table 1.

From Table 1, the variation ranges of the parameters of 90 coal samples measured are as follows: M_{ad} is 0.48–9.31%, A_{ad} is 2.71–70.73%, V_{daf} is 5.33–55.91%, TRD is 1.33–2.27 g.cm^{-3}, ARD is 1.28–2.11 g.cm^{-3}, F is 2.19–13.04%, Q_0 is 1.4558–7.4993 cm^3.g^{-1}, a is 12.6231–38.2783 cm^3.g^{-1}, b is 0.6361–1.76294 MPa^{-1}, Δp is 4–43 mmHg, and f is 0.15–1.80. From the distribution characteristics of the measured data, the selected coal samples are universal and extensive.

3 Results analysis

3.1 Multivariate nonlinear regression theory

In general, multivariate nonlinear regression is defined as follows: based on the fact that the nonlinear function has multiple derivatives in the independent variable range, the nonlinear function relationship between multivariate independent variables and dependent variables is established by transforming the nonlinear relationship into a generalized linear relationship and carrying out regression analysis by means of mathematical statistics. The general nonlinear regression model can be expressed as follows:

TABLE 1 Measured 90 coal sample coal quality index and gas basic parameters summary table (part).

Coal sample	Mine name	M_{ad} %	A_{ad} %	V_{daf} %	TRD $g{\cdot}cm^{-3}$	ARD $g{\cdot}cm^{-3}$	F %	Q_0 $cm^3{\cdot}g^{-1}$	A $cm^3{\cdot}g^{-1}$	b MPa^{-1}	Δp mmHg	f
M01	Henan Xinzheng Mine	0.58	12.05	13.52	1.47	1.42	3.40	4.0085	25.6144	1.2688	42	0.15
M02	Shanxi Yonghong Mine	2.61	17.98	33.60	1.50	1.45	3.33	2.6982	22.1144	0.9817	17	1.30
M03	Guizhou Zhenxing Mine	1.22	23.95	10.69	1.64	1.57	4.27	5.8196	38.2783	1.4789	43	0.48
M04	Shanxi Kunning Mine	0.87	12.31	12.84	1.40	1.34	4.29	4.3761	33.7181	1.1888	27	0.24
M05	Liaoning Hongyang Mine	0.81	34.43	21.95	1.66	1.58	4.82	3.6928	26.3673	1.1886	15	0.81
M06	Xinjiang Xinyesheng Mine	4.92	5.49	48.00	1.37	1.28	6.57	2.5006	22.5661	0.8398	26	1.30
M07	Jilin Yingcheng Mine	2.58	9.66	39.45	1.37	1.33	2.92	2.9286	22.5736	1.0573	10	0.58
M08	Qinghai Yuka Mine	5.27	26.34	43.68	1.64	1.53	6.71	2.6769	28.4856	0.7558	8	0.40
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
M89	Anhui Liuzhuang Mine	1.73	19.42	37.18	1.52	1.46	3.95	2.5993	18.7401	1.1558	9	0.93
M90	Yunnan Yuwang Mine	1.18	44.49	11.34	1.84	1.74	5.43	5.1137	33.2336	1.4580	25	1.60

$$y = f(x, c) + \varepsilon \tag{1}$$

In the equation, x represents observable random independent variables; c represents parameter vectors to be estimated; y represents independent observation variables; ε represents random variables. Eq. 1 is often used to solve the estimated value of the parameters using the least square method to minimize the sum of squares of the residual. The sum of squares function of residual error and its first derivative are:

$$\begin{cases} S(c) = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n} [y_i - f(X_i, c)]^2 \\ \dfrac{dS}{dc} = 2[y_i - f(X_i, c)]\left(-\dfrac{df(X_i, c)}{dc}\right) = 0 \end{cases} \tag{2}$$

The c of the above equation can be solved by calculating the Equation 2, and the global minimum can be estimated.

3.2 The determination of curvilinear equation

Taking gas adsorption constants a and b as dependent variables, 9 factors such as M_{ad}, A_{ad}, V_{daf}, TRD, ARD, F, Q_0, Δp, and f as independent variables, and 90 coal mine sample data in Table 1 as samples, the curve equation which is most suitable for gas adsorption constants a, b and related parameters is determined by using chart construction program and curve estimation in SPSS data software. After eliminating the independent variable whose fitting coefficient R^2 is less than 0.300, the curve estimation results of a and two independent variables Q_0, Δp as well as b and two independent variables V_{daf}, ARD are obtained are shown in Table 2.

From Table 2, for a and b, five commonly used unary curve equations such as linear, logarithmic, quadratic, power and index are established respectively. By comparing the coefficient of determination R^2 and significance level Sig of the five curves, it is known that the adjustment of conic $R^2 = 0.717$ fitted by a and Q_0 is the largest, and the significance level $Sig. = 0.482 > 0.05$. This shows that the quadratic curve is not significant, while the adjustment of logarithmic curve equation $R^2 = 0.711$ is larger. The significance level $Sig.$ is $0.000 < 0.05$. Therefore, a logarithmic curve equation is established for a and Q_0. The adjustment of quadratic curve equation $R^2 = 0.523$ fitted by a and Δp is the largest, significance level $Sig. = 0.003 < 0.05$. Therefore, a quadratic curve equation is established for a and Δp, and the adjustment of logarithmic curve equation fitted by b and V_{daf} is 0.698, significance level $Sig. = 0.000 < 0.05$. Therefore, a logarithmic curve equation is established for b and V_{daf}. The adjustment of quadratic curve equation $R^2 = 0.378$ fitted by b and ARD is the largest, and the significance level is $0.000 < 0.05$. Therefore, a quadratic curve equation is established for b and ARD.

3.3 Establishment of multivariate nonlinear regression model

Let the gas adsorption constant a be the equal of the dependent variable $f_i\,(i = 1, 2)$ and b the dependent variable $f_i\,(i = 3, 4)$, the atmospheric adsorption capacity Q_0 be the equal of x_1, the initial velocity of gas emission Δp be the equal of x_2, the volatile matter of coal V_{daf} be the equal of x_3 and the apparent density of coal ARD be the equal of x_4. The nonlinear regression was carried out by

TABLE 2 Estimated results of gas adsorption constants *a* and *b* curves.

Equation	a and Q_0 fitting curve		a and Δp fitting curve		b and V_{daf} fitting curve		b and ARD fitting curve	
	R^2	*Sig.*	R^2	*Sig.*	R^2	*Sig.*	R^2	*Sig.*
Linear	0.633	0.000	0.478	0.000	0.638	0.000	0.131	0.469
Logarithm	**0.711**	**0.000**	0.510	0.707	**0.698**	**0.000**	0.161	0.000
Quadratic	0.717	0.482	**0.523**	**0.003**	0.676	0.001	**0.378**	**0.000**
Power	0.684	0.000	0.514	0.000	0.677	0.000	0.128	0.000
Index	0.579	0.000	0.452	0.000	0.642	0.000	0.100	0.001

The meaning of the bold values is that the basis is used to judge the most suitable fitting equation between *a* and Q_0, a and *Δp*, *b* and V_{daf}, and *b* and *ARD*. R^2 is the decision coefficient. *Sig.* is the significance level. The bigger the R^2 value is, the better the fitting effect is, and the *Sig.* value should be less than 0.05.

using SPSS data analysis software, and the nonlinear regression Equation 3 was obtained after 9, 2, 5, and 8 iterations respectively.

$$\begin{cases} f_1 = 7.850 + 16.292\ln x_1 \\ f_2 = 11.378 + 1.151x_2 - 0.015x_2^2 \\ f_3 = 2.238 - 0.383\ln x_3 \\ f_4 = -7.641 + 10.621x_4 - 3.145x_4^2 \end{cases} \tag{3}$$

The gas adsorption constants *a* and *b* are taken as dependent variables and f_1, f_2, f_3 and f_4 as independent variables respectively, and the linear regression model of Equation 4 is obtained.

$$\begin{cases} a = -3.576 + 0.7861f_1 + 0.348f_2 \\ b = -0.208 + 0.851f_3 + 0.351f_4 \end{cases} \tag{4}$$

After testing, the decision coefficients R^2 of *a* and *b* are 0.737 and 0.728 respectively, indicating that f_1 and f_2 can explain 73.7% of the changes of the dependent variable *a* and 72.8% of the changes of the dependent variable *b*, as well as high goodness of fit of regression. The significance level (the probability value corresponding to *t* statistics) is *Sig.* = 0.002 < 0.05, *Sig.* = 0.029 < 0.05 respectively, which suggests that there is a significant correlation between independent variables and dependent variables. Durbin-Watson values of 1.617 and 2.034 are close to 2, respectively, which suggests that the sequences are independent of each other and there is no autocorrelation. The maximum variance expansion factor (VIF) is 2.112 and 1.483 respectively, which is less than 5, which suggests that there is no strong multicollinearity among independent variables.

The multiple nonlinear regression models of *a* and *b* are obtained by putting f_1, f_2, f_3, and f_4 into Equation 4, as shown in Eq. 5.

$$\begin{cases} a = 6.5536 + 12.8055\ln Q_0 + 0.4005\Delta p - 0.0052\Delta p^2 \\ b = -0.9855 - 0.3259\ln V_{daf} + 3.728ARD - 1.1039ARD^2 \end{cases} \tag{5}$$

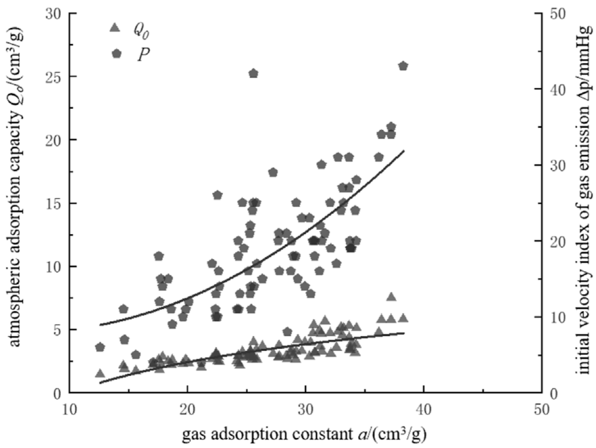

FIGURE 2
Relationship between parameters Q_0, Δp and *a* in 90 coal samples.

3.4 The influence of Q_0-Δp correlation on *a*

Atmospheric adsorption capacity, also known as residual gas capacity, refers to the maximum gas capacity of coal adsorption under atmospheric pressure. In the laboratory, the degassing method is used to make the coal sample in the state of negative pressure, and then make the coal sample adsorb methane gas at atmospheric pressure to reach adsorption saturation. Atmospheric adsorption is an important part of the prediction of gas emission from mining face, and it is also one of the prevention and control indexes of coal and gas outburst (Wu et al., 2011; Lu et al., 2022). Both an and a characterize the adsorption and desorption performance of coal, the difference between them is that the adsorption pressure is different, the adsorption pressure is standard atmospheric pressure, and the adsorption pressure of an is the limit.

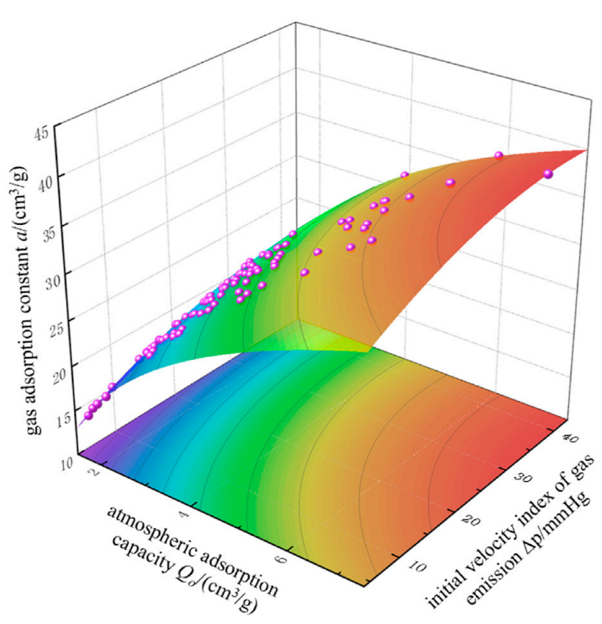

FIGURE 3
Surface fitting plot with gas adsorption constant a and Q_0-Δp

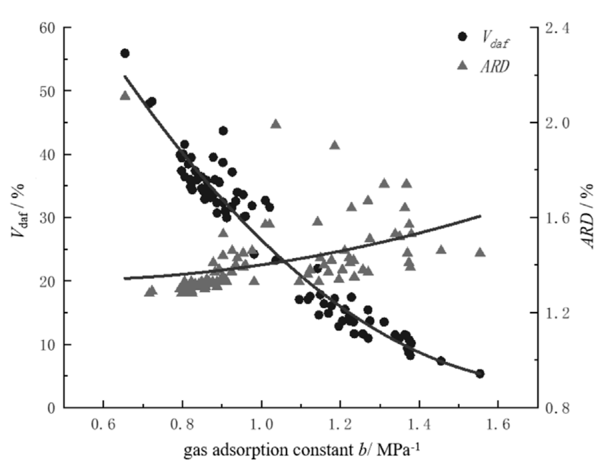

FIGURE 4
Relationship between parameters V_{daf}, ARD and b in 90 coal samples.

Figure 2 shows the overall variation trend of a under different Q_0 and different Δp. With the increase of Q_0, a shows an obvious increasing trend. And when Q_0 increases to a certain extent, the increasing amplitude of a decreases gradually and tends to reach the limit state. This is because the adsorption capacity of coal is determined by the specific surface area of coal. Under the same conditions, the larger the Q_0, the stronger the adsorption capacity of coal. The gas adsorption constant a is an index to measure the gas adsorption capacity of coal. The larger the specific surface area is, the stronger the adsorption capacity is, the greater the a is. Under the same conditions, the adsorption capacity of coal increases with the increase of gas pressure, that is, the greater the Q_0, the greater the a. When Q_0 increases to a certain extent, the specific surface area of coal decreases gradually with the increase of adsorption capacity, the ability of coal to adsorb methane weakens gradually, the growth rate of adsorption gas gradually slows down, and a gradually reaches the limit.

The initial gas emission velocity of coal represents the gas release capacity of coal at the moment of pressure relief. In Figure 2, with the increase of Δp, a shows the trend of quadratic function from low to high to low, and most coal samples increase with the increase of Δp before the extreme point. This is because the size of Δp first depends on the strength of coal adsorption capacity, and under the same gas pressure, the coal with larger specific surface area has a larger amount of gas adsorbed. Under the condition of the same gas pressure, the gas released by the coal with good adsorption performance is larger than that released by the coal with relatively poor adsorption performance (Tang, 2014; Saghafi, 2017; Si et al., 2021b). That is to say, the greater the initial velocity Δp of the gas released by the coal body in the same period of time, the stronger the adsorption performance of the coal body under the same conditions, and the greater the a. However, after the extreme point, very few kinds of coal decrease with the increase of Δp, which may be due to the fact that the coal sample is relatively dry and the water content is very low during the preparation of a few coal samples, the particle size of the prepared coal sample may be more concentrated near 0.25 mm, the particle size of the coal sample with a certain mass is relatively larger, the total pore volume is also relatively large, and the gas migration channel in coal is unobstructed. The initial amount of gas desorption is also relatively large in the same period of time (Zhao and Niu, 2022). However, when determining the gas adsorption constant a, the quantity of this coal sample will decrease with the increase of particle size at a certain mass, and the total specific surface area can be considered to maintain invariable. Therefore, a will not increase with the increase of coal sample particle size, and the adsorption saturation time may be prolonged due to the increase of coal sample particle size. This explains why a decreases with the increase of Δp after the extreme point.

According to the multivariate nonlinear regression equation5, a curved surface fitting diagram of the influence of atmospheric pressure adsorption capacity Q_0 and gas emission initial velocity on gas adsorption constant a is established, as shown in Figure 3. The influence of Q_0 on a shows an upward curve, that is, when Δp is in the range of 4–38 mmHg, a increases significantly with the increase of Δp. when Δp is in the range of 39–43 mmHg, a shows a decreasing trend with the increase of Q_0, but the decreasing trend is not obvious. The three-dimensional curved surface reflects the evolution process from trough to peak, that is, the change process of specific surface area of coal and gas pressure.

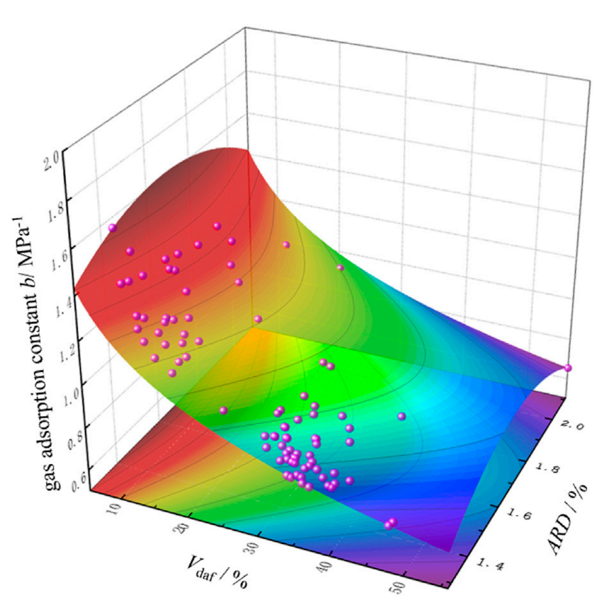

FIGURE 5
Surface fitting plot with gas adsorption constant *b* and V_{daf} -*ARD*.

3.5 The influence of V_{daf} - *ARD* correlation on *b*

The gas adsorption constant *b* characterizes the speed of coal adsorption and desorption of gas. The overall change law of *b* under different volatile matter V_{daf} and apparent density *ARD* can be seen from Figure 4. With the increase of volatile matter V_{daf}, *b* attenuates as a logarithmic function, and when V_{daf} increases to a certain extent, *b* decreases to a minimum. This is because V_{daf} characterizes the metamorphic degree of coal, and the larger the V_{daf}, the lower the metamorphic degree of coal, the weaker the adsorption capacity of coal, the slower the adsorption speed, and the longer the time to reach adsorption saturation, the smaller the *b*. On the contrary, the smaller the V_{daf}, the stronger the adsorption capacity of coal, the faster the adsorption speed, and the shorter the time to reach the adsorption saturation state, the greater the *b*. With the increase of apparent density *ARD*, *b* shows the trend of quadratic function from low to high and from high to low. This is because *ARD* characterizes the pore volume of coal. When *ARD* increases, the pore volume of coal increases, the pore size of coal increases, the gas escape channel becomes shorter, the resistance to gas desorption decreases, and the desorption rate increases, *b* increases accordingly. When *ARD* increases to a certain extent, some types of coal may change due to higher degree of coal metamorphism, the arrangement of coal molecular structure changes from disorder arrangement to neat arrangement, the pore volume decreases rapidly, the gas desorption path lengthens with higher resistance, *b* decreases accordingly.

According to the multivariate nonlinear regression model (5), a surface fitting diagram of the effect of coal volatile matter V_{daf} and coal apparent density *ARD* on gas adsorption constant *b* is established, as shown in Figure 5. The impact trend of V_{daf} on *b* is in a shape of downward curve, that is, when *ARD* is in the range of 1.28–1.69 g/cm^3, the metamorphic degree of coal decreases with the increase of V_{daf}, and the *b* value increases significantly with the increase of V_{daf}. when *ARD* is in the range of 1.70–2.11 g/cm^3, with the increase of V_{daf}, the metamorphic degree of coal decreases significantly. The three-dimensional curved surface reflects the influence of V_{daf} - *ARD* correlation on the evolution of *b* from peak to valley, that is, the pore volume of coal changes from high to low and low to high.

4 Discussion on the prediction of coal seam gas content

The most commonly used indirect method of determining coal seam gas content both domestically and internationally is to calculate the coal seam gas content according to the known coal seam gas pressure and the gas adsorption constant of coal measured in the laboratory. The equation is as follows:

TABLE 3 Comparison of the deviation between the predicted value and measured value of coal seam gas content.

Coal sample	Mine name	M_{ad} %	A_d %	V_{daf} %	ARD g·cm^{-3}	F %	Q_0 cm^3·g^{-1}	Δp mmHg	p MPa	W m^3·t^{-1}	W' m^3·t^{-1}	Absolute error rate/%
M91	Shanxi Daping Mine	0.88	9.45	11.65	1.40	3.57	4.7231	25	0.66	10.6711	10.8181	1.38
M92	Guizhou Shuiyang Mine	1.07	24.14	10.12	1.63	6.13	4.9253	20	0.66	8.8950	9.4193	5.89
M93	Guizhou Gaopo Mine	1.59	13.47	7.35	1.55	4.52	5.5315	42	0.35	7.1102	7.1920	1.15
M94	Shanxi Xishangzhuang Mine	0.66	31.93	10.63	1.63	17.79	6.5835	13	0.91	15.2126	12.5951	17.21
M95	Halagou Mine, Inner Mongolia	7.82	8.44	34.05	1.48	11.49	3.9024	15	0.24	1.7955	1.5593	13.16
M96	Guizhou Jinpo Mine	2.42	16.50	34.05	1.61	7.45	6.0866	42	0.38	5.9618	6.5657	10.13

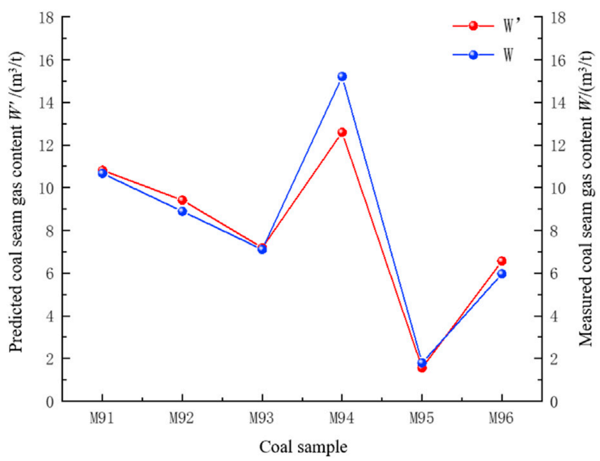

FIGURE 6
Comparison of predicted value W' and measured value W of coal seam gas content.

$$W = \frac{abp}{1+bp} \times \frac{100 - A_{ad} - M_{ad}}{100} \times \frac{1}{1+0.31M_{ad}} + \frac{10pF}{ARD \times k} \tag{6}$$

Through the above experimental study, the multiple nonlinear regression model of gas adsorption constant a and b is obtained, and the mathematical model of gas content in coal seam W' is obtained by replacing Eqn 5 with (6), as shown in Eq. 7.

$$W' = f\left(p, M_{ad}, A_{ad}, V_{daf}, ARD, F, Q_0, \Delta P\right) \tag{7}$$

From the Eqn 7, the gas content in coal seam is in connection with both gas pressure in coal seam and the seven indexes of coal quality index and gas basic parameters. The measurement of these seven indexes in the laboratory features simple operation, low cost and short time, and the test can be completed within 24 h. This greatly improves the measurement efficiency and reduces the measurement cost, and provides a solution to the problem that some coal samples cannot be determined by indirect method due to negative values of gas adsorption constant. Six coal samples were taken from 6 coal mines in Shanxi, Guizhou and Inner Mongolia provinces, and the coal quality indexes and gas basic parameters of 6 coal samples were measured in the laboratory. The coal seam gas content is predicted by using the mathematical model of coal seam absolute gas pressure p and coal seam gas content in 6 coal mines, and the predicted values W' are compared with the measured values W as shown in Table 3.

From Table 3, when the absolute coal seam gas pressure of Shanxi Daping Mine, Guizhou Shuiyang Mine, Guizhou Gaocheng Mine, Shanxi Xishangzhuang Mine, Inner Mongolia Halagou Mine and Guizhou Jinpo Mine are 0.66MPa, 0.66MPa, 0.35MPa, 0.91MPa, 0.24MPa and 0.38 MPa respectively, the range of predicted and measured coal seam gas content is 1.795–15.2126 m^3/t. The maximum absolute deviation between predicted value and measured value is 2.6175 m^3/t, the minimum absolute deviation is 0.0818 m^3/t, and the average absolute deviation is 0.7018 m^3/t. The maximum absolute error rate is 17.21%, the minimum absolute error rate is 1.15%, and the average absolute error rate is 8.15%.

From Figure 6, the broken line change trend of the predicted value W' of coal seam gas content in 6 coal mines tends to be consistent with the measured value W, especially in Shanxi Daping Coal Mine, Guizhou Gaopo Coal Mine and Inner Mongolia Halagou Coal Mine, and the two broken lines are close to coincidence, which meets the prediction requirements, indicating high accuracy and reliability of the coal seam gas content prediction model.

5 Conclusion

In this paper, the gas basic parameters and coal quality indexes of 90 coal samples from 90 coal mines in 13 provinces of China are determined, and a prediction model of coal seam gas content based on gas basic parameters and coal quality index is established. The following conclusions are mainly obtained:

1) Through the test of gas basic parameters and coal quality index of 90 coal mine samples, the curve estimation and multiple linear regression of the test data are carried out by using SPSS data software, and the multiple nonlinear regression models of gas adsorption constant a and Q_0-Δp correlation, b and V_{daf} -ARD correlation are established.
2) The effects of single factor Q_0, V_{daf} and ARD on gas adsorption constant a and b is analyzed theoretically. On this basis, a further analysis reveals that the influence of Q_0-Δp correlation on gas adsorption constant a is largely due to the change process of coal adsorption and gas release capacity from low to high, and the influence of V_{daf} -ARD correlation on gas adsorption constant b is largely due to the change process of coal pore volume from high to low.
3) The prediction model of coal seam gas content based on gas basic parameters and coal quality index is established. Seven indexes in the model can be used to complete the experimental test within 24 h, which improves the measurement efficiency and reduces the measurement cost, and provides a solution to the problem that some coal samples cannot be determined by indirect method due to negative values of gas adsorption constant. Through the comparison

between the predicted values *W'* and the measured values *W* of the six coal samples, the average absolute error rate of *W'* is 8.15%, which meets the prediction requirements. It follows from the above analysis that coal seam gas content prediction model is of instructive significance.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

LD, HL, and RF contributed to conception and design of the study. HL and XC organized the experimental data. LD and HL performed the statistical analysis. LD and HL wrote the first draft of the manuscript. XC and RL wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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