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Study on the critical value of gas content in regional prediction of coal and gas outburst based on gas adsorption and desorption experiment

Owing to the gas content is an important indicator in coal and gas outburst prevention, we set up a gas adsorption and desorption experimental system with temperature controlling, and draw out a method combining with experimental analysis, theoretical calculation and project inspection to determine the critical value of gas content in coal and gas outburst prediction. This paper takes D6 coal seam in Pingdingshan No.1 coal mine as an example, sets up the powder function equations among the gas content, gas pressure and gas desorption of drill-cuttings (Δh_2). The gas content minimum is calculated as 5.04m^3/t as the gas pressure and Δh_2 reach their critical values respectively, which is lower than the critical value of gas content (5.19m^3/t) determined by Langmuir formula, considering a deformed coal with a thickness of 0.6m exists in D6 coal seam, the critical value of gas content is determined as 5.0 m^3/t finally, and its accuracy is proved well in engineering application.

Keywords: *Coal and gas outburst, critical value of gas content, gas adsorption-desorption experiment, basic gas parameters, deformed coal.*

Introduction

Gas content in coal seam has been used as an effective checking index of coal and gas outburst prevention or regional prediction. Whether the critical value of gas content is accurately determined is of great importance in improving the accuracy of regional prediction and the reliability of effective checking in coal and gas outburst prevention [1]. According to Regulation of the Prevention of Coal and Gas Outbursts in China, each coal and gas outburst mine should determine its critical value of gas content through experimental investigation. Before the investigation, the mine takes the critical value of gas content as 8.0m^3/t temporarily in effective checking of coal and gas outburst prevention. At present, most coal mines always totally take 8.0m^3/t as the critical value of gas content without any experimental investigation in China, which may cause certain hidden danger [2]. The higher determined critical value of gas content leads to coal and gas outburst accident easily and brings the extreme economic loss for the mine safety; the lower determined critical value is not only increases coal and gas outburst prevention workload but also not reaches the total production requirement [3].

There are three common methods to determine the critical value of gas content: (1) The critical value of gas content was directly applied according to Regulation of the Prevention of Coal and Gas Outbursts. Due to the diversity of coal seams' occurrence conditions in different mines, it could bring certain hidden danger if different mines applied uniform critical value of gas content in coal and gas outburst prevention [4]. (2) Based on numerous measurement of gas content in mines, the critical value was defined with statistical analysis method. But for the new mine or where coal and gas outburst rarely occurring, this method is difficult to define the critical value [5] owing to lack of effective statistical data. (3) It can be reckoned out the critical value through Langmuir formula or the empirical formulas proposed by former researchers. When this method is applied, the accuracies and reliabilities of gas pressure, coal quality and other indicators must be pre-analysis, and the determined critical value of gas content must be verified through actual production.

In recent years, mathematical regression analyzing based on gas adsorption and desorption experiment data is used by some scholars to research the critical value of predictive index of coal and gas outburst, which is not only a new method

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including experiment and theoretical analysis, but also reveals the correlation among those predictive indexes. It is of great significance to the determination of the critical value of predictive index. Cheng et al used this method to research the correlation between drill-cuttings gas desorption (Δh_2) and gas pressure, and then determined the critical value of Δh_2 [6, 7]. Wang et al study the correlation between gas content and gas pressure by this method, and then worked out gas content's critical value [8]. This paper takes the D6 coal seam in Ping Dingshan No.1 coal mine as an example. Simulating the process of gas desorption during coal mining by gas adsorption and desorption in laboratory, we set up the mathematical relationship among gas content and gas pressure, Δh_2, and determine the critical value of gas content in D6 coal seam.

2. Experimental system and method

2.1. Gas adsorption and desorption

According to the relative research [9], there are some good relevance between gas content and pressure. Gas desorption index of drill-cuttings (Δh_2) can reflect the changes of gas content and pressure as the coal structure is substantially the same. These correlations among gas content, gas pressure and Δh_2 are researched in this experiment, and this paper uses the critical value of gas content to describe coal and gas outburst danger of working face in coal mine.

The gas adsorption and desorption experimental system was set up according to coal isothermal experimental method under high pressure. The experimental system is shown in Figs.1 and 2. It consists of degassing unit, inflatable unit, temperature control unit and gas adsorption and desorption unit. Degassing unit is used for pumping vacuum for the entire system, which including vacuum meter 7 and vacuum pump 8. Inflatable unit is used for pumping gas into the system, which includes high-pressure methane bottle 3 and

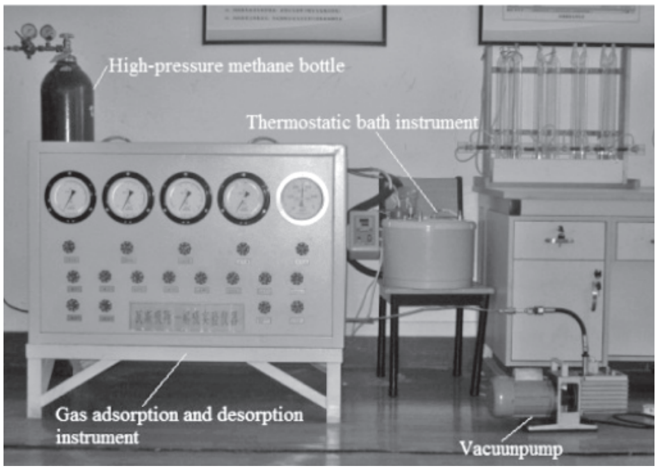

Fig.1 Facility of simulated experiment for gas adsorption and desorption

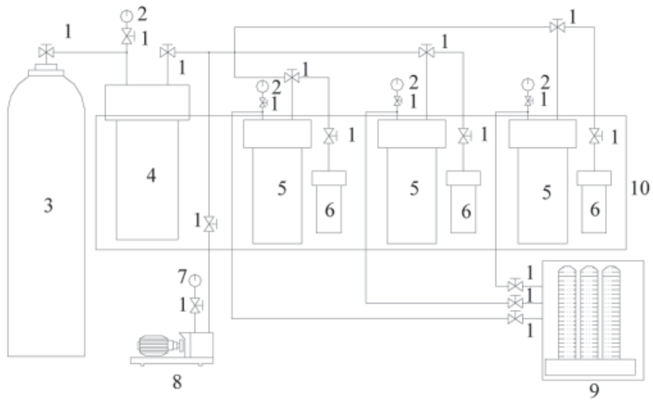

Fig.2 Schematic diagram of gas adsorption and desorption experiment. (1) High-pressure cut-off valve; (2) Accurate pressure meter; (3) High-pressure methane bottle; (4) Gas tank; (5) Big coal sample tank; (6) Small coal sample tank; (7) Vacuum meter; (8) Vacuum pump; (9) Desorption instrument; (10) Thermostatic bath

gas tank 4. Temperature control unit is used for maintaining a constant temperature, which includes thermostatic bath 10 and super thermostat. Gas adsorption and desorption unit is used for researching gas adsorption and desorption laws of coal sample, which includes big and small coal sample tank (5, 6) and desorption instrument.

2.2. Experiment method

2.2.1. Coal sample preparation

Coal's gas adsorption constant (a) is limiting gas adsorption capacity of unit mass of coal. Coal's gas adsorption constant (b) is an index which could reflect coal's gas adsorption velocity. Usually, the values of a and b are used to represent coal's gas adsorption ability. Taking some coal sample to measure the parameters of consistent coefficient (f), initial speed of methane diffusion (ΔP) and coal's gas adsorption constants (a and b). Grinding the coal sample and filtering out the coal powder whose particle size various from 0.18 to 0.25mm, which are put into grinding jars with different labels in order to sealing, and each coal sample's weight is less than 1500g.

2.2.2. Vacuum degassing and gas inflating

After checking air tightness of the experimental system, using vacuum pump to degas the entire system for more than 10 hours, and stop degasing until the vacuum meter maintains the pressure at 20Pa for 2 hours. Opening thermostatic bath and adjusting the temperature at 25°C, and then opening the high-pressure methane bottle to inflate gas into coal sample tanks. As the time of gas adsorption equilibrium exceeds 12 hours and the pressure meters' measurements keep steady for 2 hours, the gas pressure of coal sample tanks should be relived rapidly. When coal sample tanks' gas pressure decrease to 0, opening the valves to connect the desorption instrument, and then the coal samples' gas desorption should be measured and recorded with the time changing as it is exposing in the air.

Table 1: Measurements of various basic gas parameters of different coal samples

Number	Site	Destructive type	f	ΔP /%	a /$m^3 \cdot t^{-1}$	b /MPa^{-1}	M_{ad} /%	A_d /%	γ /$g \cdot cm^3$	K /%
X11278	32060 roadway	□	0.69	1.50	20.903	0.652	1.39	8.61	1.15	7.41
X11283	32060 roadway	□	0.13	8.90	24.561	0.578	1.84	18.31	1.38	8.61
X11279	32010 roadway	□	0.76	2.00	19.378	0.517	1.17	11.81	1.29	7.86
X11280	32010 roadway	□	0.15	10.30	22.466	0.482	1.21	12.17	1.22	7.69

2.2.3. Gas adsorption and desorption experiment

According to Fig.1, connecting the vacuum bag and desorption instrument well, opening the valves of vacuum bags to make the free state gas in coal sample tanks flowing into vacuum bags. When the coal samples' gas pressure reaches to zero, close the vacuum bags' valves and open gas desorption instrument's valve to make gas desorption activity of the coal samples starting. Meanwhile, using stopwatch to measure experiment time, the gas desorption value should be recorded per 5 seconds in 120 minutes. The survival gas content of coal samples should be measured until the gas desorption stops.

3. Preliminary determinations on the critical value of gas content

3.1. Measurement of basic gas parameters

D6 coal seam in Ping Dingshan No.1 coal mine belongs to outburst coal seam. This research totally takes 4 groups of coal samples with different destructive types, and measured D6 coal seams' basic gas parameters such as the adsorption constants (a and b), volatile (V_{daf}), moisture content (M_{ad}), ash content (A_d), apparent density (γ), porosity (K), consistent coefficient (f) and initial speed of methane diffusion (ΔP), the measured results are shown in Table 1.

Through observing the coal roadway underground, the coal of D6 coal seam is harder on the whole. Based on comparative analyzing the initial speed of methane diffusion of the hard and soft coals in D6 coal seam, we conclude that the soft coal's initial speed of gas diffusion is faster and the soft coal is easier to occur coal and gas outburst.

According to Table 1, the value of gas adsorption constant (a) varies from 19.378 to 24.561m^3/t, and its average is 21.848m^3/t; the value of gas adsorption constant (b) varies from 0.482 to 0.652MPa^{-1}, and the average is 0.542 MPa^{-1}, in D6 coal seam of Ping Dingshan No.1 coal mine. From the measurements of the adsorption constants, the gas adsorption capacity of D6 coal seam is weak, and the gas adsorption capacity of the soft coal is higher than that of hard coal.

3.2. Reliability analysis of the critical value of gas pressure

Based on statistical analysis on basic gas parameters of Beipiao, Jiaozuo, Hunan, Chongqing and other 26 mining areas in China, Yu Qixiang et al draw out a conclusion that there was an good correlation among the gas pressure minimum, consistent coefficient minimum and coal's volatile [10], as shown in equation (1):

$$P_{\min} = 0.58+5 \quad V_{daf} \bullet f_{\min} \quad \text{...} \quad (1)$$

where P_{min} is the critical value of gas pressure in first outburst, MPa; V_{daf} is the coal's volatile, %; f_{min} is consistent coefficient minimum of the soft coal.

According to test results of the coal of D6 coal seam in the laboratory, the value of the coal volatile varies from 28.12 to 37.25%, using the minimum value which is 28.12%; the value of coal's consistent coefficient varies from 0.11 to 0.76, using the minimum value which is 0.11; through the formula 1 the critical value of gas content is calculated as 0.76MPa, which is closed to 0.74MPa which is the critical value of gas pressure in Regulation of the Prevention of Coal and Gas Outbursts. During the production period underground, as the gas pressure is less than 0.74MPa and the Δh_2 is less than 200Pa which is the critical value of Δh_2 in the regulation, there are no gas dynamic phenomenon happening such as jet orifice, pushing-drill etc. Therefore, taking the critical value of gas pressure in D6 coal seam as 0.74MPa is reliable.

3.3. Preliminary determination on the critical value of gas content

Based on the measurement and calculation method of gas pressure which is drawn out in Basic Requirements for Gas Drainage in Coal Mine, gas pressure and gas content can be calculated by Langmuir equation mutually, as shown in equation (2). The critical value of gas content could be gained as the critical value of gas pressure is substituted into the formula:

$$W = \frac{abP}{1+bP} \times \frac{100-A_d-M_{ad}}{100} \times \frac{1}{1+0.31M_{ad}} + \frac{10\pi P}{\gamma} \quad \text{...} \quad (2)$$

where W is gas content of the coal seam, m^3/t; P is gas pressure of the coal seam, MPa; a and b are gas adsorption constants, m^3/t; M_{ad} is the coal's moisture content, %; A_d is the coal's ash content, %; π is the porosity, m^3/m^3; γ is coal bulk density, t /m^3.

According to measurements of basic gas parameters such as gas adsorption constants, porosity and others as shown in Table 1, substituting them into the equation to calculate the gas content of D6 coal seam are 5.19, 6.19, 5.25 and 5.72 m^3/t respectively when the gas pressure is 0.74MPa, the average is 5.56 m^3/t and the lowest is 5.19 m^3/t. Therefore, the critical value of gas content in Ding 6 coal seam could be determined as 5.19m^3/t preliminary.

4. Experimental results and analysis

4.1. Experimental analysis on the relationship between gas content and gas pressure

The relationship of gas content and gas pressure in coal seam is generally satisfied with the Langmuir equation, but the equation is based on an monolayer adsorption model, and the process of coal gas adsorption is influenced by the temperature, moisture, ash et al. in fact, what is more, there would be some errors in the calculation of gas content or gas pressure by Langmuir equation. Therefore, the experimental method is used to research the relationship between gas pressure and gas content. Under the constant temperature condition which is maintained at 25ºC, using the experimental system as shown in Fig.1, methane with different gas pressure is injected into the coal sample tanks. Gas desorption experiment starts after the coal samples reach gas adsorption equilibrium, and then gas desorption characteristics of coal samples under different gas adsorption equilibrium pressures could be studied (Fig.3) is the gas desorption curves of X11283 coal sample). The total gas content under certain equilibrium pressure consists of the coal sample's gas desorption and survival gas content measured after gas desorbing completely. Therefore, we could gain the coal samples' gas content under different equilibrium pressure.

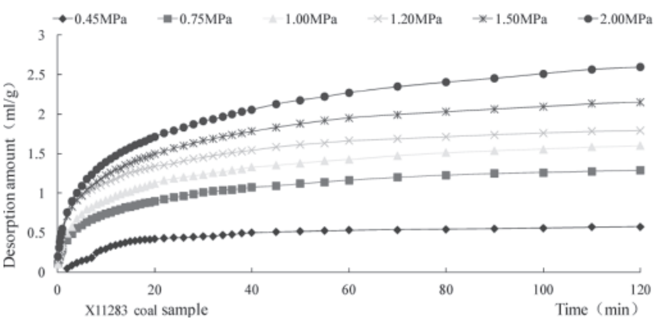

Fig.3 Gas desorption curves of X11283 coal sample under different equilibrium pressure

Fig.3 is the gas desorption curves of X11283 coal sample under different equilibrium pressure. Equilibrium pressure ranges from 0.45 to 2.0 MPa. Gas desorption time is setting as 2 hours, and the gas desorption amount ranges from 0.64 to 2.59 ml/g. As shown in the figure, with the increase of the equilibrium pressure, gas desorption quantity of the coal increases obviously. Gas desorption velocity is more quickly in the first 10 minutes, and then slows down gradually with time, almost reaches the utmost desorbed quantity after 2 hours.

As shown in Fig.4, gas pressure ranges from 0.45 to 2.0 MPa. Gas content of X11283 coal sample ranges from 3.15 to 8.42m^3/t, and that of X11280 coal sample ranges from 3.26 to 8.96m^3/t. With the increase of gas pressure, gas content of coal samples increases obviously. Furthermore, gas content increase rate slows down gradually with gas pressure growing. Based on the gas content measurements of the two coal samples under different gas pressure, mathematical regression equations between the two parameters through data fitting satisfy the power function relationship with high non-linear fit coefficients (R^2) of 0.98 and 0.87, which are shown respectively as follows: $W = 6.089P^{0.5496}$; $W = 5.929P^{0.5394}$. Through those equations, gas content of the two coal samples are calculated as 5.16 and 5.04 m^3/t respectively when gas pressure reaches its critical value of 0.74MPa.

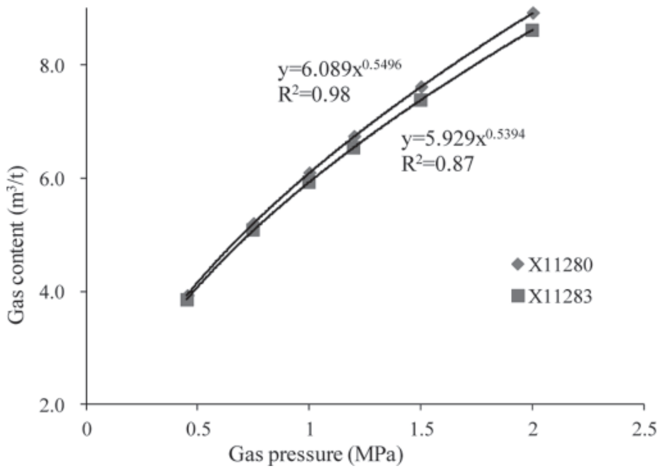

Fig.4 Fitting curves between gas pressure and gas content of different coal samples

4.2. Study on the relationships between gas content and desorption Index of drill-cuttings Δh_2

4.2.1. *Theoretical study of gas content and* Δh_2

According to the researches of Wuyi Cheng and Youan Wang from Fushun Research Institute [11, 12], there is a certain relationship between gas desorption index of drill-cutting Δh_2 and gas adsorption equilibrium pressure, as shown in formula (3):

$$\Delta h_2 = AP^B K^C \quad \text{...} \quad (3)$$

where Δh_2 is gas desorption index of drill-cutting, Pa; P is equilibrium pressure of gas adsorption, MPa; K is a comprehensive index of coal and gas outburst, K = $\Delta P/f$; A, B and C are the constants which are relative to coal metamorphism.

Studying the adsorption-desorption law of the coal samples under different gas adsorption pressure through experimental method, the constants of formula (3) could be determined and then we can get the powder function equation between gas desorption index of drill-cuttings and gas pressure.

Professor Shining Zhou, of China University of Mining and Technology, shows that there is a relationship between the gas content and gas pressure as shown in formula (4) when the gas pressure is greater than 0.2MPa through experimental study:

$$W = \alpha\sqrt{P} \quad \text{...} \quad (4)$$

where W is gas content, m^3/t; α is correlation coefficient of gas content in the coal seam, $m^3/(m^3 \cdot MPa^{1/2})$; P is gas pressure, MPa.

The formula (5) could be gained by combining formula (3) with (4):

$$\Delta h_2 = A\left[\frac{W}{\alpha}\right]^{2B} K^C \quad \text{...} \quad (5)$$

The correlation coefficient α in the same coal seam could be regarded as a constant. According to the relative data in Table 1, we could gain that the values of K are 68.46 and 68.66, which are almost the same. So K could be regarded as a constant, and formula (5) could be simplified to formula (6):

$$\Delta h_2 = EW^{2B} \quad \text{...} \quad (6)$$

From the above, there is a powder function relationship between the gas content and gas desorption index of drill-cutting, which provides the theoretical basis for determination on the critical of gas content.

4.2.2. Experimental study between gas content and Δh_2

Gas desorption index of drill-cutting Δh_2 is the gas desorption of the coal weighted 10g within the initial 3-5 minutes after relieving the equilibrium gas pressure. The value of Δh_2 could be figured out by the following formula:

$$\Delta h_2 = 10Q_{3\sim5}/0.083 \quad \text{...} \quad (7)$$

where $Q_{3\sim5}$ is the gas desorption within the initial 3-5 minutes, ml/g.

Based on the data of the coal sample during gas desorption, the relationship between Δh_2 and gas content could be worked out by the method as follows. Firstly, the gas desorption within 3-5 minutes starting at a certain time (t) is gained by the desorption experiment; The value of Δh_2 at the time t is calculated by the formula (7). Secondly, the gas content at the time t contains the gas desorption and survival gas content.

As shown in Fig.5, gas desorption of drill-cuttings (Δh_2) ranges from 80 to 340 Pa. Gas content of X11283 coal sample ranges from 3.15 to 8.42m^3/t, and that of X11280 coal sample ranges from 3.26 to 8.96m^3/t. With the increase of Δh_2, gas content of coal samples increases obviously. Furthermore, gas content increase rate slows down gradually with Δh_2 growing. Based on the gas content measurements of the two coal samples under different Δh_2, mathematical regression equations between the two parameters through data fitting satisfy the power function relationship with high non-linear fit coefficients (R^2) of 0.93 and 0.88, which are shown respectively as follows: W = 0.055 $(\Delta h_2)^{0.8609}$; W = 0.056 $(\Delta h_2)^{0.8504}$. Through those equations, gas content of the two coal samples are calculated as 5.27and 5.07 m^3/t respectively when Δh_2 reaches its critical value of 200 Pa.

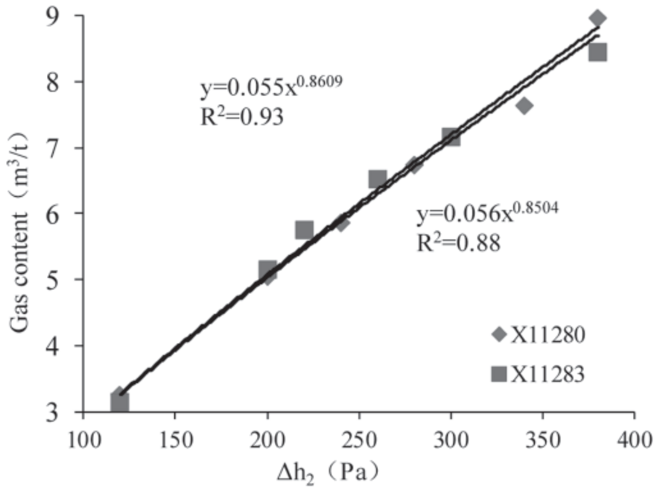

Fig.5 Fitting curves between Δh_2 and gas content of different coal samples

4.2.3. Determination on the critical value of gas content

In this paper, there are also three methods using to calculate the critical value of gas content except Regulation of the Prevention of Coal and Gas Outbursts, and the results are shown in Table 2. Furthermore, deformed coal distribution is an important factor of coal and gas outburst, which must be considered in the determination of the critical value of gas content of D6 coal seam in Ping Dingshan No.1 mine.

TABLE 2: THE CRITICAL VALUES OF PREDICTIVE INDEXES DETERMINED BY DIFFERENT METHOD

Critical values of predictive indexes			Using method
W /$m^3 \cdot t^{-1}$	P/MPa	Δh_2/Pa	
8	0.74	200	Regulation of the prevention of coal and gas outbursts
5.19	0.74	-	Langmuir equation
5.04	0.74	-	Mathematical regression equation between W and P
5.07	-	200	Mathematical regression equation between W and Δh_2

(1) In accordance with the Langmuir equation to calculate the gas content as the gas pressure is 0.74MPa, it is gained that the corresponding values of gas content varies from 5.19 to 5.72m^3/t and its minimum is 5.19 m^3/t, in D6 coal seam of Ping Dingshan No.1 coal mine.

(2) After setting up the equation between gas content and gas pressure by experiments researching, the gas content of D6 coal seam could be calculated out as the gas pressure is 0.74MPa, whose values are between 5.16 and 5.04 m^3/t.

(3) Studying the relationship between gas desorption index of drill-cuttings Δh_2 and gas pressure by experiments, and then the gas content of D6 coal seam could be calculated

out as gas desorption index of drill-cuttings Δh_2 is 200Pa, whose values are 5.27 and 5.07 m^3/t, the minimum is 5.07 m^3/t.

(4) Based on the coal roadways observation, there is a stratification of deformed coal with 0.6m in thickness in D6 coal seam, which increases the risk of coal and gas outburst of D6 coal seam under the same gas pressure.

In summary, it is determined that the minimum of gas content in D6 coal seam are 5.04, 5.07 and 5.19 m^3/t respectively by those three methods, which are lower than 8 m^3/t of Regulation of the Prevention of Coal and Gas Outbursts, and the minimum value we chose is 5.04 m^3/t among them. Since the deformed coal is well developed in D6 coal seam, which has a bigger risk of coal and gas outburst, so taking certain safety coefficient into consideration, we determine the critical value of gas content in D6 coal seam as $5m^3/t$.

5. Producing verification

All working faces in D6 coal seam of Ping Dingshan No.1 coal mine during the driving construction and mining period are managed according to Regulation of the Prevention of Coal and Gas Outbursts. Regional forecast and effective checking indicators in working faces should be measured regularly. Collecting and arranging the measurements of gas content and effective checking indicators such as drilling gas inrush initial velocity (*q*), the maximum of drill-cuttings (*S*) and gas desorption of drill-cuttings (Δh_2) in D6 coal seam, but this paper only select a part of the data as shown in Table 3.

TABLE 3: MEASUREMENTS OF GAS PARAMETERS IN DAILY WORK OF COAL AND GAS OUTBURST PREVENTION

Test site	Effective checking indicators			W /$m^3 \cdot t^{-1}$
	Δh_2 /Pa	q /$L \cdot min^{-1}$	S_{max} /$Kg \cdot m^{-1}$	
Gas drainage roadway 32030	100	3.2	4.3	2.82
Gas drainage roadway 32030	200	4.7	6.0	5.23
Return airway 32030	220	5.3	5.7	6.56
Transportation roadway in D2 mining area	120	3.6	5.1	4.23
Return airway in D2 mining area	180	5.1	6.3	5.32

Based on Regulation of the Prevention of Coal and Gas Outbursts, the values of effective checking indicators of *q* and *S* are 5L/min and 6kg/m respectively. According to Table 2, there are three groups of effective checking indicators exceeding their critical values, and the corresponding gas content values vary from 5.23 to 6.56 m^3/t, which are all more than the determined critical value of gas content. Therefore, determining the critical value of gas content in D6 coal seam as $5.0m^3/t$ is reasonable. Meanwhile, according to the drilling construction records, gas dynamic phenomenons including jet orifice and pushing-drill are occurred in those places where three groups of effective checking indicators exceed their critical values. However, no gas dynamic phenomenons happening in the places where the gas content values is lower than $5.23m^3/t$. A conclusion could be gained that the gas content measurements are more than $5.0m^3/t$ in the places where effective checking indicators of *q* and *S* are almost over standard. Thus, the determined critical value of gas content which is $5.0m^3/t$ is accurate in D6 coal seam of Ping Dingshan No.1 coal mine.

6. Conclusions

(1) Based on gas adsorption and desorption experiment of the coal samples in D6 coal seam of Ping Dingshan No.1 coal mine, it is found that mathematical regression equation between gas content and gas pressure or gas desorption index of drill-cuttings (Δh_2) satisfies power function by data fitting, which proposes a new method to determine the critical value of gas content.

(2) Comparing and analyzing the research by 4 methods of the regulation, Langmuir equation, mathematical regression equation between *W* and *P*, mathematical regression equation between W and Δh_2, we could draw out that the corresponding gas content values calculated by those methods are 8, 5.19, 5.04, $5.07m^3/t$ respectively, and the minimum value we chose is $5.04m^3/t$. Considering deformed coal is well developed in D6 coal seam, so taking certain safety coefficient into consideration, the critical value of gas content was determined as $5m^3/t$ finally.

(3) Based on statistical analysis of effect checking indexes (*q*, *S*, *W*) during mining period in D2 mining area of Ping Dingshan No.1 coal mine. The results show that all the effective check indexes are exceeding standard of gas dynamic phenomenons including jet orifice and pushing-drill happening, which proved that the determined critical value of gas content was accurate.

Conflict of interest

The authors confirm that this article content has no conflict of interest.

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