ORIGINAL PAPER

Influence of the injected water on gas outburst disasters in coal mine

Xiangjun Chen · Yuanping Cheng

Abstract The measurement of the injecting water into coal is commonly used to prevent and control methane disasters, which will increase moisture in the coal, and the characteristics of methane desorption in coal will be changed. The methane desorption of different metamorphic degree coal was tested after injecting water on homemade device. The results show that the methane desorption quantity gradually decreased with the amount of injected water. The maximum effect was obtained from the DL coal (a decrease of 82.48 % after injecting water compared with the dry sample), and moderate effects were obtained from the QN coal and the YH coal, and the lowest effect was obtained from the GJZ coal (a decrease of 37.97–47.59 % after injecting water compared with the dry sample). The impact of the injected water on the methane desorption velocity is obvious in the first 40 min, and the methane diffusion coefficient decreases gradually with the amount of injected water. The injected water can reduce the gas outburst disasters by impacting on the methane desorption quantity, methane desorption velocity, and methane diffusion coefficient.

Keywords Injected water · Gas outburst disasters · Methane desorption · Methane desorption quantity · Methane diffusion coefficient

1 Introduction

There are two main states in which methane occurs in coal: absorption and free (Clarkson and Marc Bustin 1996). The majority of methane is adsorbed (Gray 1987). When the methane pressure decreases in the coal pore, the methane will be converted from adsorption state to the free state. Many researches show that the coal physical properties

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and external environment impact the methane desorption after the decrease in methane pressure (Éttinger 1990, 1991; Le et al. 2012; Siriwardane et al. 2009; Somerton et al. 1975). With the smaller particle size of coal and higher temperature, the methane desorption speed is more larger (Yang and Wang 1986; Charrière et al. 2010). In addition, the relationship between methane desorption speed and coal rank can be described as "U" type (Zhang et al. 2011a). Methane is the catastrophic gas for coal mines, and the methane can cause people asphyxia and explosion hazards. When the methane pressures and content are high in coal seam, it will be prone to cause coal and gas outbursts, and it have threats to the safety of coal mines (Guo et al. 2009; Karacan and Okandan 2000; Karacan et al. 2011; Qin et al. 2011). In addition, coal dust is also a serious threat to the physical health of employees in coal mines. To reduce or eliminate methane and dust hazards in the mining process, some technical measures, including the injecting water, hydraulic punching, hydraulic scour, hydraulic cutting, hydraulic fracturing, and hydraulic extrusion, have been implemented before coal seam mining. After implementation of these technical measures, the moisture is increased in the coal seam. However, the increased moisture resulting from the injected water is different from the inherent moisture of coal seam, and it is extra increased moisture. Many scholars have performed studies on the influence of moisture on methane desorption (Xie et al. 2011; Zhang and Sang 2009), but they wet the coal samples before the experiment. However, the fact that a large number of methane existed in coal seam before injecting water was ignored. After injecting water, the original equilibrium state of absorption and desorption will be broken, and it makes very large differences between the experimental process and engineering practice. Therefore, it is very difficult to accurately explain the problems in engineering practice. Some scholars realized this problem (Pakowski et al. 2011; Xiao and Wang 2011; Zhang et al. 2011a; Zhao et al. 2011), and they perfected the experimental process in which water was injected into the dry coal samples under the equilibrium state of absorption methane. These researchers ensured that the experiment process was in accordance with engineering practice. However, only a single coal was used in the experiment, and the universality conclusion was difficult to determine. When injecting water into a coal sample in the experimental process, it was difficult to humidify the coal samples equitably under their experimental conditions and device constrains. Based on the engineering practice, this study developed a set of desorption test device, and the device could stir the coal samples during injecting water under high adsorption pressure, and it could improve the wet effect of the coal samples. On the device, the desorption processes of four different metamorphic degrees coal samples were tested under different adsorption equilibrium pressures and injected water. According to the desorption data, the influences of injected water on the methane desorption in the coal were studied to improve the basic theory of the injected water on methane desorption. Also, in many countries, to prevent the coal and gas outburst, injected water and gas drainage before mining coal seam were often used together, and this research can enrich the theory of coal and gas outburst prevention.

2 Methods

2.1 Coal samples and preparation

Four coal samples with different metamorphic degrees were used in the study, and these coal samples were obtained from the following locations: The YH coal was from Yonhong Mine in Shanxi Province, the GJZ coal was from Gaojiazhuang Mine in Shanxi Province,

the QN coal was from Qinan Mine in Anhui Province, and the DL coal was from Dalong Mine in Liaoning Province. According to the method using to prepare coal samples (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and Standardization administration of the People's Republic of China 2008a), the coal samples were crushed to various sizes: less than 0.2, 0.2–0.25, and 1–3 mm.

2.2 Proximate analysis

The particle size of the proximate analysis was less than 0.2 mm. Following the MT/T 1087-2008 test methods for the proximate analysis of coal, the 5E-MAG6600 proximate analyzer was used for the proximate analysis based on thermogravimetric analysis (China State Administration of Work Safety 2009).

2.3 Petrographic analysis

We prepared coal samples of 0.2–0.25-mm to determine the maceral group composition, minerals, and reflectance of the vitrinite in the coal. The maceral group composition and minerals in the coal were determined according to the GB/T 8899-1998 method for the determination of the maceral group composition and minerals in coal (State Bureau of Quality Technology Supervision of the People's Republic of China 1998), and the reflectance of the vitrinite in the coal was determined according to the GB/T 6948-2008 method for the microscopic determining of the reflectance of vitrinite in coal (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and Standardization administration of the People's Republic of China 2008b).

2.4 Analysis of pore size distribution

Currently, there are various classifications for the pore size of coal. Based on the solid pore diameter range and the solid–gas interaction effect, Dr. B. B. Hawdort divided the coal pores into four types: micropore (<10 nm, constituting the adsorption volume in coal), pore (10–100 nm, constituting condensation in the capillary and the gas diffusion space), mesopore (100–1,000 nm, constituting a slow laminar flow seepage space), and macropore (>1,000 nm, constituting an intense laminar flow seepage space).

The mercury porosimetry is the most widely used. Because mercury cannot moisten all of the solids, the mercury-injecting volume is an external pressure function. Thus, under a continuous pressure increase, the injected volume of mercury into the samples can be obtained, and the pore size distribution of the samples can be calculated. The AUTO-PORE9505 mercury injection apparatus (United States Mike Instrument Corporation) was used to determine the pore size distribution in this experiment.

2.5 Methane adsorption test

Using high-pressure volumetric equipment based on the static volumetric theory (Sing et al. 1982), the methane adsorption isotherm of 0.2–0.25 mm coal samples was tested according to the MT/T752-1997 method (China Department of Coal Industry 1997). After being dried at 378 K for 5 h in an infrared drying oven, the coal samples were cooled to

room temperature and then placed into the coal sample tank. The volumetric method was used to test the methane adsorption isotherm at 303 K.

2.6 Impact of injected water on methane desorption in coal

To study the impact of injected water on the methane desorption in coal, we developed a test device that could stir the coal samples during injecting water under the state of high-pressure adsorption. The device developed improved the wet effect of the coal sample. A schematic diagram of the experimental device is shown in Fig. 1.

The experiments were performed with 1–3-mm coal samples according to the following steps:

1. Drying the coal samples. After being dried at 378 K for 5 h in infrared drying oven, the coal samples were cooled to room temperature and then placed into a drying vessel.

2. Coal sample degassing. First, 60 g of the dry coal samples was weighed and placed into the coal sample container, and the airtight container was placed in a thermostatic oil bath at 333 K. The vacuum pump was turned on to deaerate.

3. Methane adsorption equilibrium. The temperature of thermostatic oil bath was adjusted to 303 K, and then the high-pressure methane was filled into the coal sample tank. Finally, by adjusting the valve of the coal sample tank the methane pressure reached the test pressure.

4. Injecting water into coal. First, the apparatus used for injecting water and agitating. The coal samples were stirred in the tank throughout injecting water. The quantity of the injected water was determined according to the intended experiment. To ensure wetting the coal samples, the agitation apparatus continued to stir the coal for an additional 30 min after injecting water. The adsorption equilibrium pressure and the atmospheric pressure of the experimental environment were recorded when the methane reached re-adsorption equilibrium.

5. Desorption. The valves of the coal sample tank and the desorption device were opened, and the free methane enters the gas bag. When the pressure of the coal sample tank
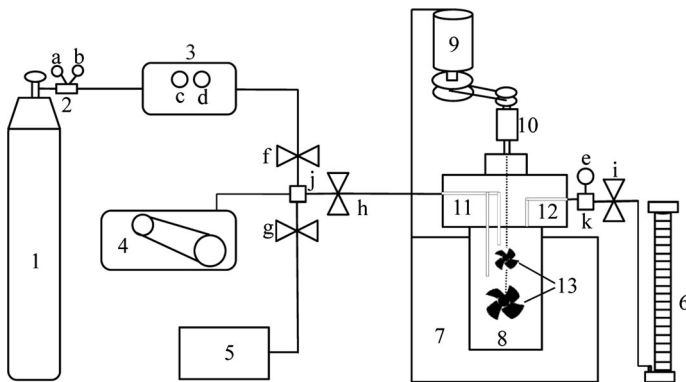

Fig. 1 Schematic diagram of the experiment device. *1* High-pressure CH₄, *2* reducing valve, *3* reference tank, *4* vacuum pump, *5* advection pump, *6* burette, *7* thermostatic oil bath, *8* coal sample tank, *9* agitation motor, *10* agitation apparatus, *11* injection water and methane inlet, *12* methane outlet, *13* agitating vane, *a–e* pressure gage, *f–i* valve, *j* four-way valve, *k* three-way valve

decreased to 0 MPa, the desorbed methane was put into the metering device though turning the three-way valve, and the quantity of desorbed methane was recorded at 1-min intervals throughout the desorption process. The experiment was terminated when the quantity of desorbed methane was less than 0.001 mL/(g min) at atmospheric pressure.

6. Determination moisture. The 5E-MAG6600 analyzer was used to determine the moisture of coal samples after the experiment. After the desorption experiment, we took the coal samples from the upper, middle, and lower parts of the coal sample tank to determine the moisture, and two samples were taken from each layer. The average moisture content of the six tested samples was looked as the moisture of the tested coal sample.

7. Data processing. To compare and analyze the methane desorption data from different coal samples, the methane desorption data collected must be converted to standard conditions using the following conversion formula:

$$Q(t) = \frac{273.2}{101325T}(P_0 - 9.81h_w - P_s) \cdot Q'(t) \tag{1}$$

where $Q(t)$ is the methane desorption quantity under standard conditions at t min (mL/g), $Q'(t)$ is the methane desorption quantity under room temperature at t min (mL/g), T is the water temperature in the burette during the test (K), P_0 is the atmospheric pressure of the experimental environment (Pa), h_w is the water column height in the burette during the test (mm), and P_s is the saturated vapor pressure at temperature T (Pa).

3 Results and discussion

3.1 Proximate analysis and petrographic analysis results

The results of the proximate analysis and the petrographic analysis of the four coal samples are shown in Table 1.

3.2 Results of the adsorption test

The results of the Langmuir volume and Langmuir pressure of the coal samples are shown in Table 1.

3.3 Pore size distribution in the coal samples

We tested the pore size distribution of the four coal samples using an AUTOPORE9505 mercury injection apparatus (United States Mike Instrument Corporation). The results of the pore size distribution and the specific surface area distribution are shown in Tables 2 and 3.

3.4 Impact of the injected water on the methane desorption quantity

To study the impact of the injected water on the methane desorption in coal, we tested the methane desorption process of the YH, GJZ, QN, and DL coals under different adsorption equilibrium pressures at 303 K after injecting water with the developed device. In China, the critical value of gas pressure forecasting outburst was 0.84 MPa. Also, according to the

Table 1 Basic parameter of coal samples

Sample	Moisture (%)	Ash (%)	Volatile (%)	Vitrinite (%)	Inertinite (%)	Exinite (%)	Mineral (%)	R_{0max} (%)	Langmuir volume V_L (mL/g, daf)	Langmuir pressure P_L (MPa, daf)
YH	1.50	16.92	7.06	49.72	45.34	0	4.94	3.0493	45.2490	0.8518
GJZ	1.17	17.96	23.72	66.15	27.04	0	6.81	2.1743	23.7530	1.2048
QN	2.25	18.60	34.66	72.94	22.59	0	4.57	1.4243	34.9051	1.4122
DL	6.32	18.70	36.19	58.30	2.25	0	39.45	0.62	40.2597	1.4954

Table 2 Pore volume distribution of coal samples

Pore diameter range (nm)	Macropore (>1,000)	Mesopore (100–1,000)	Pore (10–100)	Micropore (<10)	Total
YH					
Pore volume (mL/g)	0.0275	0.0042	0.0104	0.0095	0.0516
Proportion (%)	53.29	8.14	20.16	18.41	100
GJZ					
Pore volume (mL/g)	0.0424	0.0022	0.0013	0.0185	0.0644
Proportion (%)	65.84	3.42	2.02	28.73	100
QN					
Pore volume (mL/g)	0.025	0.0018	0.0074	0.0071	0.0413
Proportion (%)	60.53	4.36	17.92	17.19	100
DL					
Pore volume (mL/g)	0.0638	0.0034	0.0146	0.0179	0.0997
Proportion (%)	63.99	3.41	14.64	17.95	100

Table 3 Specific surface area distribution of coal

Pore diameter range (nm)	Macropore (>1,000)	Mesopore (100–1,000)	Pore (10–100)	Micropore (<10)	Total
YH					
Specific surface area (m^2/g)	0.01	0.064	1.993	5.223	7.29
Proportion (%)	0.14	0.88	27.34	71.65	100.00
GJZ					
Specific surface area (m^2/g)	0.005	0.038	0.079	7.13	7.252
Proportion (%)	0.07	0.52	1.09	98.32	100
QN					
Specific surface area (m^2/g)	0.003	0.031	1.57	3.881	5.485
Proportion (%)	0.05	0.57	28.62	70.76	100
DL					
Specific surface area (m^2/g)	0.005	0.063	2.89	9.772	12.730
Proportion (%)	0.04	0.49	22.70	76.76	100

present mining depth of coal seam, gas pressure of many coal mines exceeds 0.84 MPa. Therefore, to increase the contrast of the article and consider the engineering practice, 0.5, 0.84, 1.5, 2.5 MPa were selected as the test pressures. The desorption quantity differences of YH coal with the different moisture are shown in Fig. 2, and other coals have the same or similar curves too. The pressure is the adsorption equilibrium pressure of the dry coal before injecting water in the figure.

As shown in Fig. 2, the methane desorption quantity of dry coal is higher than that measured after injecting water under 0.5 MPa during the same period. The methane desorption quantity of coal after the injecting water was significantly reduced, and the methane desorption quantity gradually decreased with the increasing amount of injected water.
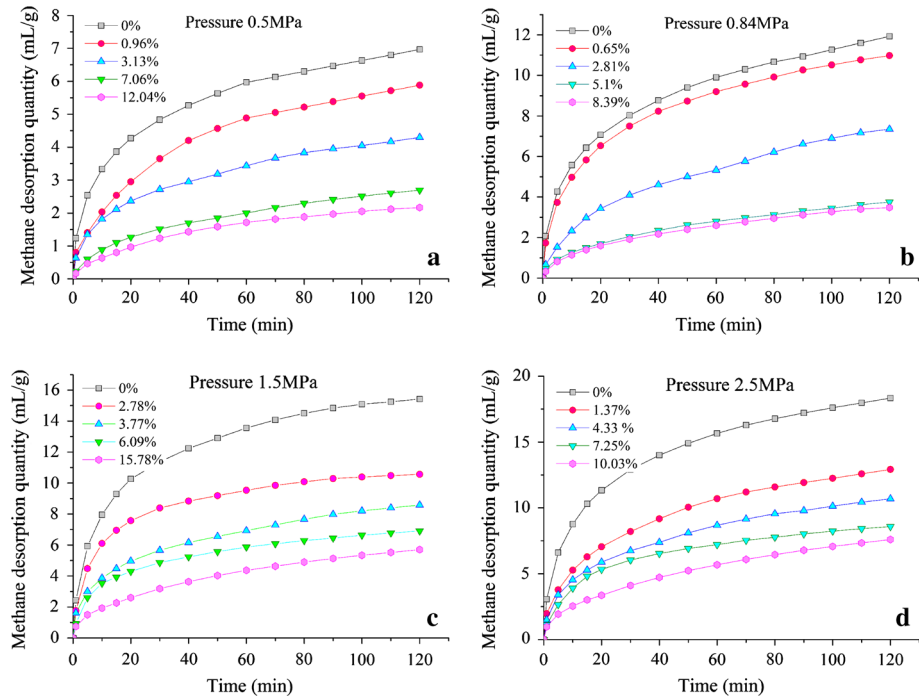
Fig. 2 Methane desorption curves for YH coal under different amounts of injected water

The curve shapes of the relationship between the methane desorption quantity and the time are similar to the Langmuir curve. Therefore, the process of methane desorption can be described by the Langmuir equation:

$$Q(t) = \frac{Q_L t}{t_L + t} \tag{2}$$

where $Q(t)$ is the methane desorption quantity at t min (mL/g), Q_L is the maximum desorption quantity (mL/g), t_L is the desorption constant (min), and t is the desorption time (min).

Based on the experimental data, the results of the regression analysis between the maximum methane desorption quantity and the time are shown in Table 4.

As shown in Table 4, the maximum desorption quantity of dry coal is the highest under the same adsorption equilibrium pressure. After injecting water, the maximum desorption quantity of the coal is decreased, and it is decreased with an increase in the volume of the injected water. The maximum desorption quantities of the YH coal after injecting water content of 0.96, 3.13, 7.06, and 12.04 % were reduced by 5.17, 35.92, 55.39, and 62.19 %. The maximum methane desorption quantity is significantly reduced with the initial increase in the volume of the injected water and then slowly reduced with further increases in the volume of the injected water. There is a critical value for the impact of the injected water on the maximum methane desorption quantity such that the impact of the injected water on the maximum methane desorption quantity is less when the volume of injected water is greater than the critical value.

Table 4 Regression model of maximum desorption quantity and injected water

Pressure (MPa)	Coal	Model	Correlation coefficient (%)	Injection water differential pressure (MPa)
0.5	YH	$Q_L = 7.2546e^{-0.0998Mad}$	96.24	3.5
	GJZ	$Q_L = 0.75e^{-0.0633Mad}$	94.90	1.5
	QN	$Q_L = 0.8108e^{-0.1421Mad}$	97.28	1.5
	DL	$Q_L = 1.9469e^{-0.1621Mad}$	95.80	1.5
0.84	YH	$Q_L = 12.7979e^{-0.1527Mad}$	96.54	3.16
	GJZ	$Q_L = 1.5117e^{-0.0767Mad}$	83.25	1.16
	QN	$Q_L = 2.0275e^{-0.1072Mad}$	93.54	1.16
	DL	$Q_L = 3.9421e^{-0.1552Mad}$	93.95	1.16
1.5	YH	$Q_L = 14.3829e^{-0.0775Mad}$	78.66	2.5
	GJZ	$Q_L = 2.6939e^{-0.061Mad}$	82.29	1.5
	QN	$Q_L = 2.4351e^{-0.1186Mad}$	98.09	1.5
	DL	$Q_L = 5.5275e^{-0.1197Mad}$	92.75	1.5
2.5	YH	$Q_L = 17.8519e^{-0.08Mad}$	92.16	1.5
	GJZ	$Q_L = 3.9161e^{-0.0527Mad}$	90.96	1.5
	QN	$Q_L = 3.4575e^{-0.0658Mad}$	78.65	1.5
	DL	$Q_L = 9.0934e^{-0.0874Mad}$	94.35	1.5

The maximum methane desorption quantity of the YH coal increases with an increase in the adsorption equilibrium pressure when the volume of injected water is similar. Compared with the dry coal samples, the maximum methane desorption quantity of the coal after injecting water content of 2.81 % is reduced by 27.41 % under 0.84 MPa, and the maximum methane desorption quantity of the coal after injecting water content of 2.78 % is reduced by 32.47 % under 1.5 MPa. Thus, the degree of influence of the injected water on the maximum methane desorption quantity is not consistent under different adsorption equilibrium pressures. As observed from the experimental results, compared with the dry coal sample, the reduced amplitude of maximum methane desorption quantity for DL coal after injecting water content of 10.94 % is highest at 82.48 % under 0.5 MPa.

The maximum methane desorption quantity for the YH coal after injecting water content of 7.06 % is 3.2733 mL/g, and the maximum methane desorption quantity for the GJZ coal after injecting water content of 4.61 % is 0.4631 mL/g. In addition, the maximum methane desorption quantity of the QN and the DL coal after injecting water content of 7.1 and 9.85 % is 0.2846 and 0.4846 mL/g. Compared with the dry coal samples, the maximum methane desorption quantity decreased by 55.39, 42.39, 64.06, and 77.84 %. Thus, the effect of the injected water on the maximum methane desorption quantity exhibits differences for different coal ranks.

The maximum methane desorption quantity decreases after injecting water under the same adsorption equilibrium pressure for all metamorphic grades coal. To analyze the influence of the injected water on the maximum methane desorption quantity of different coal ranks, the results of the regression analysis between the maximum methane desorption quantity of different coal ranks and the injected water under different adsorption equilibrium pressure are shown in Table 5.

Table 5 Regression model of maximum desorption quantity and injected water

Pressure (MPa)	Coal	Model	Correlation coefficient (%)	Injection water differential pressure (MPa)
0.5	YH	$Q_L = 7.2546e^{-0.0998Mad}$	96.24	3.5
	GJZ	$Q_L = 0.75e^{-0.0633Mad}$	94.90	1.5
	QN	$Q_L = 0.8108e^{-0.1421Mad}$	97.28	1.5
	DL	$Q_L = 1.9469e^{-0.1621Mad}$	95.80	1.5
0.84	YH	$Q_L = 12.7979e^{-0.1527Mad}$	96.54	3.16
	GJZ	$Q_L = 1.5117e^{-0.0767Mad}$	83.25	1.16
	QN	$Q_L = 2.0275e^{-0.1072Mad}$	93.54	1.16
	DL	$Q_L = 3.9421e^{-0.1552Mad}$	93.95	1.16
1.5	YH	$Q_L = 14.3829e^{-0.0775Mad}$	78.66	2.5
	GJZ	$Q_L = 2.6939e^{-0.061Mad}$	82.29	1.5
	QN	$Q_L = 2.4351e^{-0.1186Mad}$	98.09	1.5
	DL	$Q_L = 5.5275e^{-0.1197Mad}$	92.75	1.5
2.5	YH	$Q_L = 17.8519e^{-0.08Mad}$	92.16	1.5
	GJZ	$Q_L = 3.9161e^{-0.0527Mad}$	90.96	1.5
	QN	$Q_L = 3.4575e^{-0.0658Mad}$	78.65	1.5
	DL	$Q_L = 9.0934e^{-0.0874Mad}$	94.35	1.5

As shown in Table 5, the change in the maximum desorption quantity of different coals follows an exponential function with the injected water. The general form of the regressive exponential model is $Q_L = Q_0e^{-\alpha Mad}$, where Q_L is the maximum desorption quantity of coal after injecting water, Q_0 is the maximum desorption quantity of dry coal, and α is attenuation coefficient. The minus sign of α indicates that the maximum desorption quantity decreases gradually with injected water. The injected water has no effect on the maximum desorption quantity when α equals 0. The value of α characterizes the influence degree of the injected water on the maximum desorption quantity, and a greater value indicates a greater impact of the injected water on the maximum desorption quantity. Based on the experimental data, the value of α is not 0 for the YH, GJZ, QN, and DL coals under 0.5, 0.84, 1.5, and 2.5 MPa. This finding demonstrates that the injected water influences the maximum desorption quantity, and the maximum desorption quantity decreases gradually with injected water.

To analyze the relationship between the maximum desorption quantity and the differential pressures of injected water (injecting water pressure subtracted by the adsorption equilibrium pressure of dry coal) for the same coal sample under different adsorption equilibrium pressures, we analyzed the attenuation coefficient of the maximum desorption quantity for YH coal and the differential pressures of injected water under different adsorption equilibrium pressures, and the results are shown in Fig. 3.

As shown in Fig. 3, the attenuation coefficients of the maximum methane desorption quantity under 0.5, 0.84, 1.5, and 2.5 MPa are 0.09984, 0.15266, 0.0775, and 0.08, respectively, and the influence degree of the injected water on the maximum methane desorption quantity is not consistent under different adsorption equilibrium pressures. This finding demonstrates that the relationship between the influence degree of the injected water on the maximum methane desorption quantity and the differential pressure of
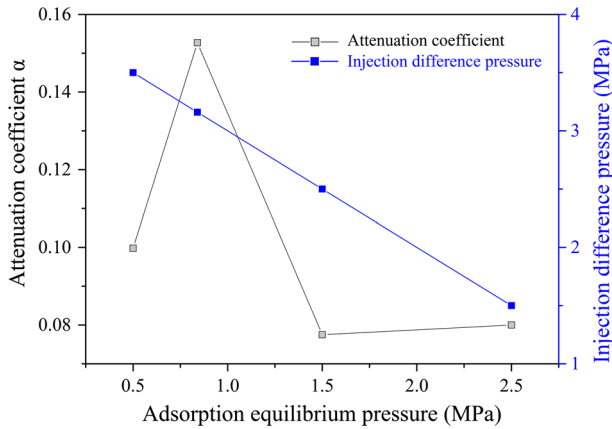
Fig. 3 Attenuation coefficient of the maximum desorption quantity and injection differential pressure for YH coal

injection water is not good. This finding is different from the results reported in the studies performed by Zhao et al. (2011), likely due to the differences in the coal samples used. Zhao used coal briquette in his experiment, and the high-pressure water could act on coal briquette directly by entering the finer pores with a differential pressure, which would impact the methane desorption. However, we used particle coal in the experiment. Thus, the pressure of high-pressure water was consumed by the pore space between the particle coal when the high-pressure water was injected into the coal sample tank, and the high-pressure water could not directly act on the particle coal. Thus, the differences in the injected water pressure had no obvious effect on the methane desorption.

To analyze the influence degree of the injected water on the maximum desorption quantity for YH, GJZ, QN, and DL coals under different adsorption equilibrium pressures, we determined the attenuation coefficient of the maximum desorption quantities under different adsorption equilibrium pressures, and the results are shown in Fig. 4.

As shown in Fig. 4, the influence degree of the injected water on the maximum desorption quantity is not consistent under different adsorption equilibrium pressures. With increasing adsorption equilibrium pressure, the influence degree of the injected water on the maximum desorption quantity for YH, GJZ, QN, and DL coals exhibits some changes, and the influence degree is not consistent. The differences are likely due to the nature of the coal sample and the uniformity effect of the injected water, and the volatility is more obvious for YH coal. In general, the influence degree of the injected water on the maximum desorption quantity decreases with an increase in the adsorption equilibrium pressure.

This trend is likely due to the fact that more methane molecules are adsorbed on the coal surface with an increase in the adsorption equilibrium pressure. As a result, the exposed areas in the coal are decreased, and the effect of water molecules on the coal surface is reduced. In addition, the metathesis of water molecules is weak, which reduces the influence degree of the injected water on the maximum methane desorption quantity. The attenuation coefficients of the maximum desorption quantity for YH, GJZ, QN, and DL coals are 0.08, 0.0527, 0.0658, and 0.0874 under 2.5 MPa. Thus, the influence degree of the injected water on the maximum desorption quantity for YH, GJZ, QN, and DL coals under the same adsorption equilibrium pressure is not consistent. The effect of the injected water on the maximum desorption quantity for DL coal is the higher, and the effect on the
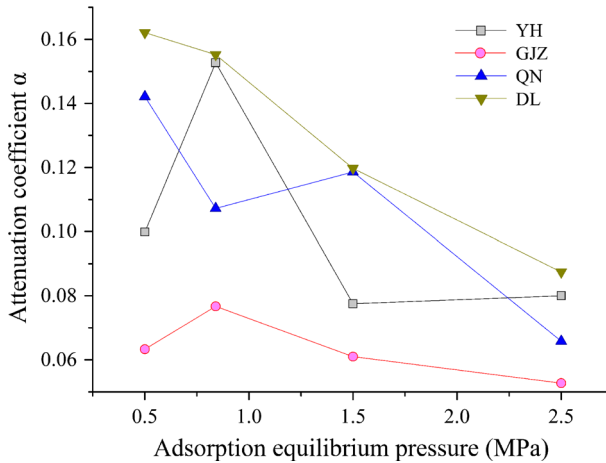
Fig. 4 Attenuation coefficient of maximum desorption quantity for different coal ranks

methane desorption quantities for QN and the YH coal are moderate, and the effect on the methane desorption quantity for GJZ coal is the lowest.

Joubert et al. (1973, 1974) thought that the effect of internal surface wetting and pore-filling is restricted by the solid–liquid surface tension in the coal pore, and the water must overcome the solid–liquid surface tension when it enters the coal matrix pore to wet the inner surface of the coal. A smaller pore size implies that the effect of the solid–liquid surface tension is greater, which indicates that it is more difficult for the water to enter the micropore, and the only macropores and outer surface in the coal are wetted. After injecting water in the coal samples, the water molecules will compete with the methane molecules for adsorption sites. Because water molecules have polarity, the water molecules will be preferentially adsorbed on the surface compared with the methane molecules (Sang et al. 2005). Therefore, the adsorbed methane molecules will be replaced by moisture molecules, and the replaced amounts of methane molecules are connected with a total specific surface area of macropores, mesopores, and pores. A larger total specific surface area of macropores, mesopores, and pores imply that a higher amount of moisture molecules will replace the methane molecules. The adsorbed methane amount is reduced when many methane molecules are replaced, which will result in a reduction in the methane adsorption quantity after pressure relief. Based on the experimental results, the total specific surface area of the macropores, mesopores, and pores for DL coal is the largest at 2.958 m^2/g. The YH, QN, and GJZ coals exhibit the second-highest, third-highest and lowest total specific surface area of macropores, mesopores, and pores, and these values are 2.067, 1.604, and 0.122 m^2/g, respectively. This ranking of the total specific surface area of macropores, mesopores, and pores is consistent with the influence degree of the injected water on the maximum desorption quantity.

3.5 Impact of the injected water on the methane desorption velocity

The curves of the methane desorption velocity for YH coal and the time are shown in Fig. 5, and other coals have the same or similar curves too.
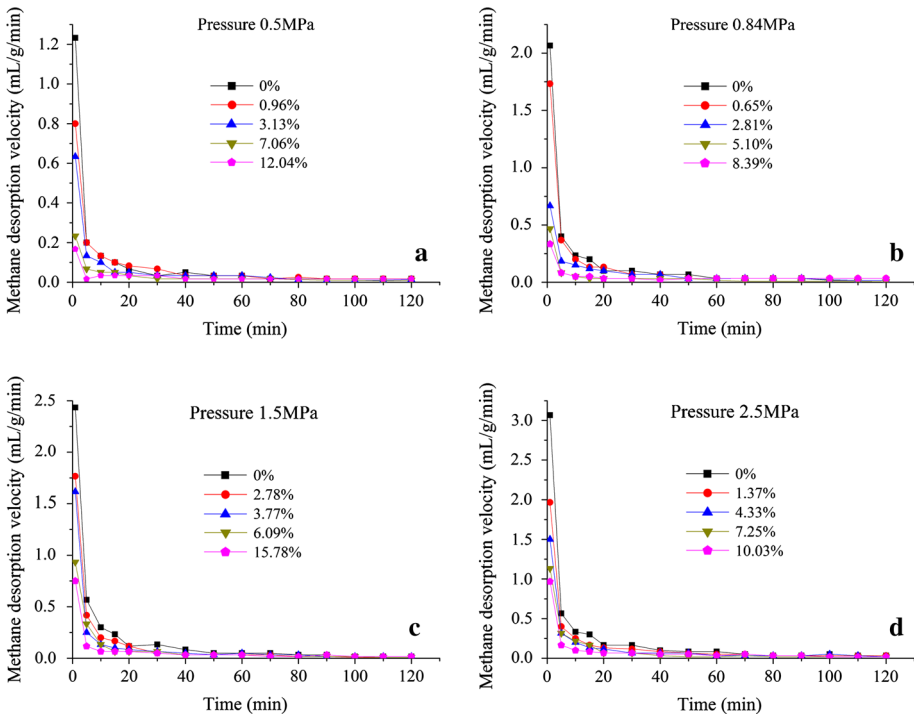
Fig. 5 Curves of methane desorption velocity for YH coal under different amounts of injected water

As shown in Fig. 5, the methane desorption velocity (methane desorption quantity in 1 min) for YH coal decreases gradually with time under the same adsorption equilibrium pressure. The initial methane desorption velocity of dry coal is the maximum, and the initial methane desorption velocity of coal after injecting water is decreased compared with dry coal. The decreased amplitude of the methane desorption velocity of dry coal is higher than that obtained from coal after injecting water. However, after 40 min, the methane desorption velocities of both of these coals (dry and wet) are roughly equal. It is clear that the impact of injected water on the methane desorption velocity is higher during the early stage and lower during the late stage. Based on the desorption data of the YH coal under 0.5, 0.84, 1.5, and 2.5 MPa, a greater pressure results in a higher methane desorption velocity of similar moisture coal at the same stage.

3.6 Impact of the injected water on the diffusion coefficient

Diffusion is a random process of fluid molecules that move from a high-concentration region to a low-concentration region under the driving influence of the concentration gradient. There exist three types of diffusion processes in porous media (Krishna and Wesselingh 1997; Siemons et al. 2007): (1) Fick diffusion mainly occurs in macropores, mesopores, and pores, and the collisions between methane molecules are the dominant mechanism, (2) Knudsen diffusion mainly occurs in micropores, and the collisions between the methane molecules and the pore walls are important, and (3) surface diffusion

Table 6 Results of methane diffusion coefficient

Pressure (MPa)	YH coal		GJZ coal		QN coal		DL coal	
	Moisture (%)	D (10^{-11} m^2/s)	Moisture (%)	D (10^{-11} m^2/s)	Moisture (%)	D (10^{-11} m^2/s)	Moisture (%)	D (10^{-11} m^2/s)
0.5	0	1.6968	0	1.4897	0	1.1438	0	2.1132
	0.96	1.1218	1.28	1.4385	2.15	1.0076	0.61	1.4790
	3.13	1.2146	3.46	1.3961	5.3	0.9343	4.69	1.5654
	7.06	0.8327	7.61	1.2260	7.1	0.8610	9.85	1.3408
	12.04	0.7611	10.21	1.1706	9.14	0.7308	10.94	1.1752
0.84	0	1.4743	0	2.0397	0	2.0309	0	0.5789
	0.65	1.3623	1.42	1.9347	2.12	1.5871	1.47	0.4706
	2.81	1.3457	3.95	1.6566	5.75	1.2892	2.24	0.4333
	5.10	1.1522	4.17	1.3914	6.71	1.1770	4.77	0.3695
	8.39	1.1348	9.81	1.2292	10.54	1.0120	10.07	0.2586
1.5	0	1.9274	0	2.0040	0	1.4517	0	0.7088
	2.78	1.5223	2.17	1.6686	2.28	1.1774	1.63	0.6093
	3.77	1.2968	3.44	1.0021	5.35	1.1903	4.76	0.5599
	6.09	1.1355	5.21	0.9369	7.51	1.0855	8.7	0.3425
	15.78	1.1207	9.43	0.7837	10.97	1.0565	11.61	0.3148
2.5	0	1.2384	0	2.1091	0	0.9623	0	1.5440
	1.37	1.2191	2.29	1.3639	1.66	0.7502	0.96	1.4597
	4.33	1.1430	6.01	1.0586	4.86	0.4499	2.81	0.7250
	5.91	1.0399	8.72	0.8562	8.89	0.3963	9.58	0.4747
	10.03	1.0155	10.47	0.7308	21.49	0.5362	11.94	0.3440

mainly occurs in microspores and pores, and this type of diffusion is between Fick diffusion and Knudsen diffusion.

Researchers have commonly used the Fick diffusion theory to describe the diffusion process of methane adsorption in porous coal. When analyzing the methane diffusion in porous media, researchers typically consider the pore shape as round, coal particles as spherical particles, and the boundary concentrations as constants. Thus, the adsorption/desorption rate formula is the following (Ni 2011; Ruckenstein et al. 1971):

$$\frac{M_t}{M_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\frac{Dn^2\pi^2t}{r^2}} \tag{3}$$

where M_t is the methane adsorption/desorption quantity in t minutes (mL/g), M_∞ is the limit of the methane adsorption/desorption quantity (mL/g), r is the radius of a spherical particle (m), and D is the diffusion coefficient (m^2/s).

We used the desorption data to calculate with Eq. (3). In our case, the value of t is equal to 120 min, M_t is the methane adsorption/desorption quantity in 120 min, and M_∞ is the measured limit of the desorption quantity. When n is greater than 10, the results only exhibit a slight change; therefore, we adopted a value of 10 for n in the calculation. The computational results of the methane diffusion coefficients are shown in Table 6.

As shown in Table 6, the diffusion coefficient for the coal after injecting water is less than the diffusion coefficient for dry coal under the same adsorption equilibrium pressure. The diffusion coefficients exhibit an overall gradually decreasing trend with an increase in the volume of injected water, and the other coal samples also exhibit this behavior. Moreover, this finding is consistent with the results obtained by Pan et al. (2010). The diffusion coefficient of the GJZ coal exhibits an increasing tendency with the pressure increase when the amount of injected water is similar, and this result is consistent with the conclusions reached by Pan and Smith (Pan et al. 2010; Smith and Williams 1984). However, the diffusion coefficients for YH, QN, and DL coals do not exhibit this clear trend, and the differences are likely related to the coal pore characteristics and the physical properties of the different coals.

4 Conclusions

This study developed a device for injecting water and desorption under the high-pressure adsorption state. It was used to test the methane desorption of different metamorphic degree coal. The results show that the accumulated quantity of methane desorption was found to increase gradually with time. The maximum desorption quantity decreases gradually with the amount of injected water. The effect of the injected water on the maximum desorption quantity was maximal for DL coal, whereas the QN and the YH coals exhibited moderate effects, and the GJZ coal exhibited the lowest effect. The effect of the injected water on the GJZ coal is 37.97–47.59 %, which is 50 % of that obtained from the DL coal. This difference is likely not due to the differential pressure of injecting water but the different total surface areas of the macropores, mesopores, and pores in the coals. The impact of the injected water on the methane desorption velocity is obvious in the first 40 min, and this impact can be ignored after 40 min. The methane diffusion coefficient decreases gradually with an increase in the amount of injected water. The injected water can reduce the gas outburst disasters by impacting on the methane desorption quantity, methane desorption velocity, and methane diffusion coefficient.

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