Research Article

Desorption and Transport of Temperature-Pressure Effect on Adsorbed Gas in Coal Samples from Zhangxiaolou Mine, China

Xiaohu Zhang,1 Wenxin Li,2,3 and Gan Li3,4

1School of Civil Engineering, Guizhou University of Engineering Science, Bijie 551700, China
2Key Laboratory of Mining Disaster Prevention and Control, Qingdao 266590, China
3State Key Laboratory of Strata Intelligent Control and Green Mining Co-Founded by Shandong Province and the Ministry of Science and Technology, Qingdao 266590, China
4Institute of Rock Mechanics, Ningbo University, Ningbo 315000, China

Correspondence should be addressed to Gan Li; ligan303@126.com

Received 7 September 2021; Accepted 19 October 2021; Published 10 November 2021

Academic Editor: Hao Liu

Copyright © 2021 Xiaohu Zhang et al. Exclusive Licensee GeoScienceWorld. Distributed under a Creative Commons Attribution License (CC BY 4.0).

The development of coal seam fissures and gas migration process caused by mining disturbance has an extremely important influence on gas control and roadway stability. In this study, the desorption, diffusion, and migration tests of adsorbed gas under the coupling effect of temperature and uniaxial compression were conducted on four coal samples from Zhangxiaolou mine, using the temperature and pressure coupling test system of deep coal rocks. The test confirms that the higher the temperature, the faster the desorption and emission of the adsorbed gases in the coal, and the larger the volume of the emitted gases. Meanwhile, it is found that the adsorbed gases in the coal samples of Zhangxiaolou mine are carbon dioxide and methane in the order of content. It is found that during the uniaxial compression process, several large negative values of the pressure of the emitted gas occur during the stable growth stage of the crack. This indicates that the crack expansion makes a new negative pressure space inside the coal sample, and the negative pressure values increase continuously during the unstable growth phase of the crack until the coal sample is destroyed. And after the axial pressure is removed, the escaped gas pressure shows a large positive value due to the rebound of the coal matrix and the continuous desorption of a large amount of adsorbed gas from the new crack location, which has a significant hysteresis with respect to the occurrence of the peak stress. Meanwhile, the SEM images of the coal samples before and after the test are analyzed to confirm the cause of the negative pressure generation.

1. Introduction

The mechanical environment of deep coal rocks is very complex, with three highs and one disturbance [1], where the three highs refer to high stress, high temperature, and high permeability, and the one disturbance refers to the disturbance force caused by mining disturbance in deep engineering. In the geological environment of “the three highs and one disturbance,” when deep coal seams are disturbed by mining, the coal and rock mass will inevitably undergo deformation and destruction and even lead to deep nonlinear dynamic disasters such as rock burst, roof collapse, and mine earthquake. According to global statistical results, mine earthquakes of magnitude 3 or greater may occur in mines mined at depths greater than 500 meters. Therefore, the effect of temperature and pressure on deep coal mines cannot be ignored.

As the mining depth increases, the gas pressure in the coal seam also increases. As the gas content increases and the coal becomes softer, the gas permeability of the coal seam decreases. Coal seam gas is not easy to be drained before mining, but during the mining process, the amount of gas released is large and the release speed is fast. Coupled with the complex geological conditions of mining coal seams, the outburst disasters of coal and gas are more serious than shallow layers. The increase in mining depth is also accompanied by an increase in the formation temperature. When the mining depth reaches 1000 m, the formation
temperature will reach 30-50°C, which may be higher in some areas, which is also extremely unfavorable for the mining face. As the temperature increases, the adsorbed gas in the coal diffuses outward, and both the diffusion coefficient and desorption rate increase with temperature. In the process of coal seam being disturbed or new cracks inoculated by mine earthquakes, the rate of gas release is amazing, which makes the occurrence of deep outburst disasters more severe than shallow ones, and the greater the depth, the more outbursts. Therefore, it is of great practical importance to study the transport law of adsorbed gas in coal under the effect of temperature-pressure coupling.

As the remains of ancient plant deposits, coal has an extremely interesting complex structure-double pore structure, which makes coal rock has a huge specific surface area, which can be calculated by the gas adsorbed on it, per unit mass of coal. The specific surface area may reach 181 m²/g. The reserves of adsorbed gas in coal are extremely rich. The dual-pore structure of coal also suggests that gas transport in coal is very different from transport in other rocks because coal expands when it adsorbs gas. Stress level, emitted gas pressure level and gas composition, coal fracture characteristics and water content are closely related to gas adsorption, desorption, diffusion, transport, and coal expansion processes. The interrelationship between coal and gas has been studied for more than a century. Siriwardane et al. [2], Somerton et al. [3], and Wang et al. [4] studied the permeability of coal gas and its evolution process through experiments. The experiment found that the gas with the same adsorption properties as coal, such as CH₄ and CO₂, is compared to those with weak adsorption (such as xenon and nitrogen) has poor permeability. Durucan and Edwards [5], Huy et al. [6], and Somerton et al. [3] found that the permeability of coal and rock decreased by five orders of magnitude when the circumferential pressure was increased from 0.1 MPa to 70 MPa. At constant pressure, the permeability of adsorbed gas also decreases with increasing pore pressure due to the expansion of the coal [7–11]. It has also been found that the permeability of adsorbed gas in coal is also a function of gas exposure time [12]. Han et al. suggested that water saturation of water content in coal also affects the permeability of coal seam gas [13]. Based on field tests as well as laboratory results, many theoretical models for coal bed gas permeability have also been proposed.

Scholars around the world have conducted a large number of studies on gas transport patterns in coal, and many models have been proposed. In 1947, Darcy’s law was first applied by Soviet scholars to describe the movement of coalbed methane. Afterward, a large number of amendments were made to Darcy’s law of transportation in coalbed methane [14–16]. Deng et al. established the equation of motion for nonlinear flow of gas in low-permeability coal seams [17].

The transport of coalbed methane is not only influenced by the structure of the coal body but also related to factors such as stress field and temperature field [18]. Zhou et al. believed that the adsorption of a large amount of gas in coal rock would reduce the effective stress, which would reduce the strength of the media [19]. In this way, under external disturbances, the coal seam would be strongly fragmented, causing strong deformation and rheology, and releasing a large amount of adsorbed gas will increase the intensity of gas protruding. Gavuga and Khodot first investigated the solid-gas coupling effect of coal and gas [20–22]. Harpalani studied the relationship between permeability and load of coal samples [23]. The transport of gas in coal is also closely related to its adsorption and desorption processes on the gas. Winter and Janas [24] concluded that the volume of gas desorbed from coal after adsorption equilibrium is closely related to the gas content in the coal, the gas pressure in the coal, the duration of desorption, the temperature, and the particle size of the coal sample. Airey [25] established the theory of gas transport of coal by studying the desorption of gas from coal. Wang and Yang [26] tested the gas desorption rate of coal samples by gravity method and concluded that the variation of gas desorption in coal with time is in accordance with Langmuir equation. The study of the behavior of pristine adsorbed gases in coal is just beginning, and current studies do not distinguish between the different effects of axial and circumferential stresses on gas emissions [27–29]. The mining-induced concentrated stress will lead to crack propagation and failure [30, 31], and these cracks will be followed through by the desorbed and emitted coal gas, so that they have a closed relationship with emitted gas pressure, and the interaction between coal gas emission and the fractures also accelerates the possibility of catastrophic failure and threat safety mining.

Although so many studies have been done on the adsorption and desorption of coal and gas, there are still few studies on the desorption, diffusion, and transport behavior of adsorbed gas in coal from the conditions of the coupling effect of temperature and pressure [32–36]. Based on the previous research results, in this study, the desorption and diffusion experiments of adsorbed gas under the coupling of temperature and pressure were carried out in the laboratory on four coal samples from Zhangxiaolou mine, and the desorption and diffusion behaviors of adsorbed gas under the coupling of temperature and pressure were described.

Considering the combined effects of increasing coal mining depth and increasing coal mine working face temperature and high ground stress, coal seam adsorptive gas keeps desorption and diffusion to the working face under the action of temperature and pressure, which seriously endangers personnel safety. Usually, it is difficult to accurately estimate the degree of influence of temperature and pressure on gas desorption, respectively, thus, making it impossible to make more accurate gas escape predictions. This paper is based on the experiment of desorption migration law of adsorbed gas under the coupling effect of temperature and pressure. The innovation of this experiment is to combine the temperature and pressure environment in which the coal samples are located and to obtain the influence law of temperature and pressure on gas desorption migration from the perspective of the experiment, and the results obtained from the experiment have important theoretical and cognitive significance for guiding the coal seam gas extraction and reducing the hidden gas hazard in coal mines.
2. Experiment Preparation

2.1. Sample Preparation. The coal samples selected in this paper are real coal and rock samples (Figure 1). The selected coal rock is taken from no. 9 coal seam of Zhangxiaolou mine in Pangzhuang coal mine at the same depth of -1025 m. The coals (size $300 \times 400 \times 450 \text{mm}^3$ and $300 \times 200 \times 250 \text{mm}^3$) were taken out on site and transported back to the laboratory. The coal sample is processed by an automatic drilling machine and an automatic double-end grinder, and standard samples of $\Phi 50(\pm 1) \text{mm} \times 100(\pm 1) \text{mm}$ were made. Gas in the coal sample is mainly divided into the adsorption gas and free gas. The coal samples will be exposed to the air for 2 weeks before the experiments began, in order to make the free gas in the coal sample escape to the outside, making that the gas existing in samples began, in order to make the free gas in the coal sample be exposed to the air for 2 weeks before the experiments began. Gas in the coal sample is mainly divided into the adsorption gas and free gas. The coal samples will be exposed to the air for 2 weeks before the experiments began, in order to make the free gas in the coal sample escape to the outside, making that the gas existing in samples only is the adsorption state, which will utmostly reduce the effects of free gas on the test results. Photographs of the coal samples before tests are shown in Figure 1. The basic parameters of the coal samples are shown in Table 1.

Zhangxiaolou mine is one of the high-temperature mines in Xuzhou mining area. The temperature of -750 m horizontal roadway reaches 28 degrees, and the highest can reach 32 degrees. The temperature in the -1000 mm horizontal roadway reached 39 degrees. The geological structure of the mine is scour zone, fault and fissure development, and geological structure has great influence on gas occurrence. The fault structure in the minefield is very complex, and there are 12 large and medium-sized faults exposed. The mine is a low-methane mine. From the perspective of fault strike, it can be roughly divided into two groups. The first group is a NE-trending fault, whose strike is consistent with the shallow anticlinal axis cut, and can be regarded as strike fault basically. The other group is NW-trending faults, which are generally orthogonal or oblique to the axial direction of the shallow anticline and are basically dip faults. Through the analysis of gas geology, it is revealed that the gas emission in Zhangxiaolou mine is relatively high at the level of -750 m, and the relative gas emission tends to decrease with the increase of mining depth and production below the level of -750 m, which is contrary to the conventional that gas increases with the mining depth. The decrease of gas emission in deep is mainly caused by sedimentary environment factors such as scouring of ancient riverbed, and the distribution of abnormal gas emission area is mainly caused by tectonic factors such as fault. It can be seen from the scanning electron microscope image in Figure 2 that the development of crack pores in coal samples provides a lot of internal conditions for gas adsorption and storage.

The coal sample was taken from the no. 9 coal seam of Zhangxiaolou mine, which is buried below -1025 m, and the temperature of the seam reached about 40 degrees. The samples selected in this article are processed from the coal blocks taken at the same site, so they reflect the real situation. Since the two coal blocks were taken from the same location, the coal samples processed from the first coal block were numbered ZX1-1#, ZX1-2#, and ZX1-3#; and the coal samples processed from the second coal block were numbered ZX2-1#, ZX2-2#, and ZX2-3# for the sake of distinc-

2.2. Experiment System. In order to study the desorption, diffusion, and transport law of these gases adsorbed in raw coal under the coupling effect of temperature and pressure, the deep coal rock gas transport experimental system was developed (Figure 3), which can not only reproduce the desorption and transport process of adsorbed gases in coal under the effect of temperature but also simulate the desorption, diffusion, and transport process of adsorbed gases in coal under the effect of pressure. In addition, the equipment can also realize the desorption and transport processes under the coupled action of temperature and pressure as mentioned above. The test system also measures the pressure of the emitted gas, the volume of the emitted gas, and the concentration content of each constituent.

The deep coal rock adsorption gas experiment system consists of three systems, which are pressure control system, temperature control system, and gas detection system. The pressure control system includes axial loading and lateral loading. Axial loading adopts XTYE-2000 hydraulic testing machine. The temperature control system includes a temperature controller, a temperature sensor, and an electric heating device. The temperature controller heats the hydraulic oil in the pressure chamber according to the oil temperature data monitored by one of the temperature sensors with accuracy of $\pm 0.1^\circ \text{C}$. The other temperature sensor directly monitors the temperature change of the coal sample itself during the heating process. The gas monitoring system and the pressure chamber are connected by metal pipes. The system mainly includes a nitrogen-hydrogen all-in-one machine and a gas chromatograph and gas pressure and flow measurement equipment. The chromatograph can detect the main components of the desorbed gas and analyze the gas composition automatically. The measurement range of gas pressure is -1000~1000 Pa, and the gas flow meter is selected according to the actual situation of coal sample ($0~5 \text{ml/min}$ for low range flow meter and $0~50 \text{ml/min}$ for high range flow meter, the low range flow meter is used in experiments). Therefore, during the experiment, information on important parameters such as composition, content, pressure, and flow rate of emitted gas can be obtained.

2.3. Experiment Procedures. This experiment focuses on the desorption, diffusion, and transport characteristics of
adsorbed gases in raw coal under the coupling effect of temperature and pressure. Two main influencing factors are considered in the experimental process: temperature and stress. Under the coupling effect of temperature and stress, the transport state of adsorbed gas in raw coal samples and the effect of cracks on gas transport during uniaxial pressure cannot be carried out by conventional test methods. The specific steps of the test are shown in Figure 4, and the detailed procedures are as follows:

1. Seal the coal sample with fluoroelastomer heat shrink tube, connect the temperature controller to the surface...
temperature sensor of coal sample will be temperature sensor, and put the coal sample into the triaxial pressure chamber

(2) Connect the oil temperature sensor to the temperature controller

(3) Use the chromatograph to detect the standard gas, if both are basically the same, it means the chromatograph is in good working condition

(4) Connect the chromatograph to the gas guide tube, connect the flow meter and chromatograph, and turn on the temperature controller and chromatograph

(5) Adjust the time of each device to be consistent, so that the experimental results have good time consistency

(6) Set the temperature target value and slowly increase the temperature with rate of 0.1°C/min. Keep the temperature constant after it reaches the target temperature value. During the heating process, test the gas composition every half hour

(7) Apply axial pressure to failure, record stress and strain at the same time, and test gas composition continuously

(8) Increase the temperature to a higher target temperature and keep it constant

(9) End the test

In this test, in order to ensure that the gas inside the coal sample is discharged from the air guide tube above, on the one hand, the coal sample was encapsulated with a fluoroelastomer heat shrink tube. The fluoroelastomer provided a better seal even during the destruction of the coal sample, which prevented the hydraulic oil from intruding into the sample and thus into the air guide tube. On the other hand, the wire of the temperature sensor on the surface of the coal sample was perforated through the heat shrink tube, and latex was used to seal the hole in order to prevent the hydraulic oil from soaking in. In addition, a gas sealing test of the system was performed by gas chromatography before the test to ensure a good gas tightness of the system during the experiment.

Because in coal mine site conditions, the temperature of the coal body is in a more constant range, and at the same time, the coal body will be constantly subject to the pressure generated by mining disturbances and other factors, this paper adopts a heating-thermostatic-uniaxial loading-heating process, and the first three steps are mainly to
simulate the real boundary conditions and initial conditions of the coal sample, which makes the test have strong engineering significance. The last step of the heating process is aimed at evaluating the volume of adsorbed gas in the coal sample at the ultimate conditions (higher temperature).

3. Results and Discussion

3.1. Experimental Results of the Whole Process. In this experiment, four cases of temperature-pressure coupled desorption tests were conducted, during which the changes of parameters such as gas pressure, escape volume, axial stress, concentration of emitted gas, and temperature of coal samples were recorded. The designed test conditions were uniaxial compression tests at thermostatic stage. Among them, the test processes of ZX1-1# and ZX1-2# are four-stage tests of initial heating-thermostatic-uniaxial loading-final heating, and the test processes of ZX2-1# and ZX2-3# are three-stage tests of initial heating-thermostatic-uniaxial loading.

Figure 5 shows the results of the temperature-pressure coupled desorption-diffusion experiment for the ZX1-1#.

Figure 5(a) shows the time course curves of the axial force applied to the coal sample and the pressure curve of the emitted gas during the experiment. It can be seen that the axial stress is applied during the thermostatic temperature of 46.6°C, while the pressure of the emitted gas fluctuates around 0, and the minimum negative value of gas pressure is -995 Pa. After 9.39 min, the gas pressure rises to positive 38 Pa. It can be found that the axial pressure loading process has a great influence on the gas escape.

Figure 5(b) shows the time course curves of the gas components and the corresponding concentrations detected during the experiment. It can be seen that the main components of the adsorbed gases in the coal samples are CH4 and CO2. It can also be seen that the concentration of desorbed gas varies with the whole experiment process. At 93.98 min, the concentration of CO2 reached 4.48%, and the concentration of CH4 reaches 0.015%, which tends to constant at the thermostatic stage. However, the concentration decreases during the axial compression loading process, and the lowest values of CO2 and CH4 concentration appear at 138.98 min, which are 0.853% and 0.002%, respectively. After the axial
compression is released, it increases rapidly in the final heating stage.

Figure 5(c) shows the cumulative volume and temperature control curves of the gases detected during the experiment. It can be seen that the experimental process is divided into four stages. The first stage is the initial heating stage with a time interval of 0 min to 43.55 min. In this stage, there is no external axial force. Under the condition of heating, the internal adsorbed gas of the coal sample will desorption and diffuse outward along the fracture network. The second stage is the thermostatic stage, and the time interval is 43.55 to 103.55 min; because the coal sample is crushed under the action of axial force, the characteristics of this stage are the concentration and the pressure of the emitted gas decrease. The time interval from 103.55 to the end corresponds to the last stage, which is characterized by the increase of porosity caused by the crushing of coal sample, thus, accelerating the desorption and diffusion of adsorbed gas at the reheating temperature. It can be seen that the amount of gas escaping is rapidly increasing.

Figure 6(a) shows the time history curve of axial force and the pressure curve of emitted gas for the coal sample during the experiment for ZX1-2#. It can be seen that the variation pattern of the emitted gas when the axial force is applied at a thermostatic temperature of 40°C is similar to that of Figure 5. At 145.71 min, the gas pressure was the minimum negative value of -442 Pa. After 10.1 min, the gas pressure increased to positive 23 Pa. Figure 6(b) shows the time history curves of the gas components and the corresponding concentrations detected in the experiment. It can be seen that the main components of the gases adsorbed in the coal sample are CH4 and CO2. It can also be seen that the concentrations continue to increase during the initial
ramp-up phase, reaching a maximum value of 0.011% and 5.46% for both CH4 and CO2 at 103 min, respectively. During the axial loading phase, the concentrations of CO2 and CH4 reach their lowest values at 133.00 min, with 1.087% and 0.004%, respectively. After the release of axial compression, the concentrations of CO2 and CH4 increase rapidly in the final heating step. Figure 6(c) shows the accumulated gas volume and temperature control curve detected during the experiment. It can be seen that the gas escape is divided into four stages. In the heating stage, the corresponding time interval is 0~47.99 min. Under the heating condition, the internal adsorbed gas of the coal sample will desorption and diffuse outward along the fracture network, and the volume of the emitted gas increases rapidly in this stage. The second stage is a thermostatic stage with a time interval of 47.99 min to 127.33 min. At this stage, the temperature is maintained at 40°C, and the volume of emitted gas rises slowly. The third stage is the axial pressure stage with a time interval of 127.33~159.97 min. In this stage, the coal sample is crushed under the action of axial force. The time interval from 159.97 to the end corresponds to the final heating stage, which is characterized by the increase of porosity caused by the crushing of coal sample, thus, accelerating the desorption of adsorbed gas at the reheating temperature.

Figure 7 shows the results of the temperature-pressure coupled desorption-diffusion experiment for the ZX2-1# coal sample. It can be seen that the test process is divided into three stages of initial heating, thermostatic stage, and uniaxial loading stage. The gas pressure variation of the coal sample is basically consistent with that shown in Figures 5 and 6, with a minimum value (~1005 Pa) at the uniaxial peak stress position (246.81 min). The concentration profile increases with temperature and reaches a maximum at the applied axial load, where the concentration of CH4 reaches 0.076% and that of CO2 reaches 31.85%. During the heating phase, the volume of the emitted gas increases linearly. After
axial force loading, the volume rate of the emitted gas accelerates significantly.

Figure 8 shows the experimental results of the temperature-pressure coupled desorption diffusion experiment of ZX2-3# coal sample, and it can be seen that its correlation curve is similar to Figure 7. The minimum value of the emitted gas pressure also occurs at the position of the stress peak corresponding to 189.33 min, with a minimum value of -687 Pa for the gas pressure. With the increasing temperature of the coal sample at 126.96 minutes, the temperature of the coal sample reached 71.3°C, and the concentrations of carbon dioxide and methane reach their maximum values of 3.215% and 0.009%, respectively. And as the test continued, the temperature of the coal sample decreases to a minimum of 69.1°C, and the decrease in temperature leads to a decrease in the desorption of the adsorbed gases and, therefore, there is a decrease in the concentration of CH4 and CO2 dioxide after reaching the peak. The concentration values of CH4 and CO2 decrease during the destabilization of the sample rupture and then increase rapidly. The volume of emitted gases increases linearly with time, with a maximum escape volume of 4.4 mL.

In this study, the fugitive gas pressure is the gas pressure detected by the gas chromatography system under the coupling effect of temperature and pressure of the coal sample. It can be seen that the main components of the gases adsorbed inside the coal sample are CO2 and CH4. It can also be seen that the concentration of the desorbed gases varies with the whole experimental process. During the initial heating phase, the concentration increases continuously. During the thermostatic stage, the concentration tends to level off, but decreases during the axial pressure loading. After the release of axial pressure, the concentration rises rapidly during the later heating phase.

Figure 8: Transport of desorbed gas from coal sample ZX2-3# under the combination of temperature and mechanics loading. (a) indicates loading path and emitted gas pressure. (b) Respective concentration of desorbed gases including methane and carbon dioxide. (c) involves temperature and volume of gas.
3.2 Heating Stage. As shown in Figures 9(a) and 9(b), the sampled gas volumes for samples ZX1-1# and ZX1-2# are 0.000342 ml and 0.00011 ml for CH4 and 0.1011 ml and 0.05519 ml for CO2, while the sampled gas volumes for samples ZX2-1# and ZX2-3# are 0.01066 ml and 0.0001125 ml for CH4. The volume of gas detected increases with increasing temperature, while the increase in desorption implies a decrease in the adsorption capacity of the coal. The concentration of the detected gas also increases with increasing temperature. We found that the main component of the adsorbed gas in the coal samples from Zhangxiaolou mine was CO2, and the concentration of CO2 was generally larger than that of CH4 during the test. It can be seen that the sample with the highest temperature has the highest gas desorption rate and desorption amount, so the desorption rate is very sensitive to temperature. In addition, the escape gas pressure behaves more complex than the other parameters, but we find that more positive gas pressure occurs at faster temperature increases. At isothermal conditions, all parameters change very slowly. The negative gas pressure with very low amplitude can be explained as follows: the adsorbed gas molecules desorb in a discontinuous manner, which means that the gas molecules are dragged by molecular forces in one way and struggle to escape in another way in Brownian motion under thermodynamic equilibrium. Thus, the gas flows in channel in a pulsating manner.

3.3 Uniaxial Loading Stage. Figures 10 and 11 show the relationship curves between the stress-time curve and the escape gas pressure during uniaxial compression. According to
Among them, the loading process can be divided into different stages. The stress curve rises smoothly, and no new fractures are created at this stage. Stress (MPa) of emitted gas occurred during this phase, -265 Pa at 127.66 min and -64 Pa at 128.85 min. These large negative values represent the sudden appearance of cracks in the coal. They should be tension cracks, because only tension cracks can create a fast passage of gas flow, which makes the volume of coal increase. The sudden increase in pore volume in the coal causes a rapid backflow of gas to escape. As a result, a large negative gas escape pressure occurs. The maximum volumetric strain also occurs at the point of $\sigma_{cd}$. Phase IV is the unstable crack propagation stage, and $\sigma_{cd}$ is the point where the crack starts to penetrate. As can be clearly seen in Figure 10, more negative gas pressure values appear, which means more tension cracks are formed. These tension cracks are interconnected, causing the internal pores and volume of the coal and rock to increase rapidly and allowing a constant flow of gas back. When the coal sample is destabilized by fracturing, some of the cracks generated in the second and third stages keep cracking and expanding, and when the uniaxial stress reaches the peak, the cracks penetrate and the coal sample loses its integrity, while the bearing capacity decreases sharply, accelerating the redistribution of internal cracks, and the dramatic increase of crack volume strain in a split second leads to a steep decrease in the internal pressure of the coal sample, creating a large internal volume and a lower internal pressure. As a result, the maximum negative value of -995 Pa occurs within 130.11 min. With the end of axial stress, part of the sample recovered its elasticity, and more gas is desorbed and spread out along the penetrating fractures, whereupon a larger positive pressure value of 38 Pa appeared at 139.51 min.

Figure 11: Stress-gas pressure diagram of sample ZX2-1# and ZX2-3# showing the stages of crack development.

$$\varepsilon_{cv} = \varepsilon_a + 2\varepsilon_r - \frac{1 - 2\nu}{E}\sigma_{a}, \quad (1)$$

where $\varepsilon_{cv}$ is the crack volume strain, $\varepsilon_a$ is the axial strain, $\varepsilon_r$ is the radial strain, $\sigma_a$ is the axial stress, $E$ is the modulus of elasticity, and $\nu$ is the Poisson’s ratio. According to the characteristics of the crack volume strain, the whole uniaxial loading process can be divided into five loading stages. Among them, $\sigma_{ci}$ is the stress level at crack closure, $\sigma_{cf}$ is the stress level at crack initiation, $\sigma_{cd}$ is the stress level at crack propagation, and $\sigma_{cd}$ is the peak stress level.

It can be seen from Figure 10 that the whole uniaxial compression test process can be divided into five stages, while the gas pressure and the amount of emitted gas in different stages are different. The following uses ZX1-1# as an example to illustrate the characteristics of crack growth and gas transportation in a uniaxial process. As can be seen in Figure 10(a), stage I where the stress level goes from 0 to $\sigma_{ci}$ is the initial closure of the cracks inside the coal and rock samples. In this process, the coal sample undergoes elastic compression and the internal fractures close. The adsorbed gas in the coal is compressed in the mutual pores and fractures and moves along the fractures to the outside of the coal body. In Figure 10(a), the pressure of the emitted gas is more positive, and the surface gas is transported outward. The stress curve rises smoothly, and no new fractures are created at this stage.

The stress level of phase II ranges from $\sigma_{cc}$ to $\sigma_{ci}$. This stage is an elastic region. The strain detected in this region is the elastic strain of the coal matrix itself. In this region, the stress curve is approximately straight, and no new cracks are generated. Therefore, the gas pressure does not change dramatically.

Phase III is a stage where cracks grow steadily, and $\sigma_{ci}$ is called a crack point. Two large negative pressure values of emitted gas occurred during this phase, -265 Pa at 127.66 min and -64 Pa at 128.85 min. These large negative values represent the sudden appearance of cracks in the coal. They should be tension cracks, because only tension cracks can create a fast passage of gas flow, which makes the volume of coal increase. The sudden increase in pore volume in the coal causes a rapid backflow of gas to escape. As a result, a large negative gas escape pressure occurs. The maximum volumetric strain also occurs at the point of $\sigma_{cd}$.

Phase IV is the unstable crack propagation stage, and $\sigma_{cd}$ is the point where the crack starts to penetrate. As can be clearly seen in Figure 10, more negative gas pressure values appear, which means more tension cracks are formed. These tension cracks are interconnected, causing the internal pores and volume of the coal and rock to increase rapidly and allowing a constant flow of gas back. When the coal sample is destabilized by fracturing, some of the cracks generated in the second and third stages keep cracking and expanding, and when the uniaxial stress reaches the peak, the cracks penetrate and the coal sample loses its integrity, while the bearing capacity decreases sharply, accelerating the redistribution of internal cracks, and the dramatic increase of crack volume strain in a split second leads to a steep decrease in the internal pressure of the coal sample, creating a large internal volume and a lower internal pressure. As a result, the maximum negative value of -995 Pa occurs within 130.11 min. With the end of axial stress, part of the sample recovered its elasticity, and more gas is desorbed and spread out along the penetrating fractures, whereupon a larger positive pressure value of 38 Pa appeared at 139.51 min.
the first drop phenomenon, because coal is a very complicated heterogeneous body and is a porous medium, within a rich native fissure development, when the external loading and continue to increase, the original cracks will expand, first in its tip will appear airfoil extension crack, then it expands and bifurcates step by step, and then overlapped with the surrounding secondary cracks. At this time, the coal sample shows macroscopic main cracks and volume expansion.

After capacity expansion, more and more new fractures are developed in the coal body, and the fracture zone expands gradually, creating convenient channel conditions for the migration of emitted gas, so that it can continue to migrate and diffuse from the original pore fracture zone to the damaged fracture zone of the low concentration area. At this point, the phenomenon of decreasing gas pressure is shown on the macro level, and gas reflux is used to reduce the gas pressure and concentration outside the coal body. In uniaxial compression deformation, gas reflux caused by volume expansion occurs, which is also called "negative pressure effect." According to this, the sudden drop of gas concentration can be detected to predict the sudden change of pore structure of coal matrix. As the axial pressure decreases continuously, when the loading is stopped, the adsorbed gas in the coal sample matrix is continuously desorbed outward because of the formation of new cracked pore channels, and the desorbed gas continuously fills the negative pressure space. And after the gas pressure returns to zero, a positive gas pressure is finally formed with the continuous outflow of desorbed gas. Because it takes time to fill the negative pressure space, this also explains the lag in the appearance of positive gas pressure.

Also from the above analysis, it can be seen that the volume of emitted gas changes differently under the combined effect of temperature and pressure. The faster the temperature rises, the faster the volume of emitted gas rises, for example, at 197.4 min for ZX1-1#, the temperature rises at 0.39 °C/min, and the gas volume rises steeply from 0.011 ml/min to 0.14 ml/min. After the specimen is fractured, the gas volume also rises rapidly, for example, at 246.3 min for ZX2-1#, the temperature remains constant, and the gas volume rises suddenly from 0.074 ml/min to 0.21 ml/min just after the specimen is completely fractured, which was verified by Jin et al. [38].

3.5. Comparison of the Results of Each Stage. Table 2 gives the volume of emitted gas at each stage, it can be seen that for the initial ramp-up stage, the higher the thermostatic temperature, the larger the corresponding volume of emitted gas. The maximum volume of emitted gas is 1.64 ml at a thermostatic temperature of 80.7 °C, and the minimum volume of emitted gas is 0.25 ml at 40 °C. The pattern of the volume of emitted gas at the thermostatic stage is the same as that at the initial heating stage. The maximum volume of gas desorbed is 3.28 ml at a thermostatic temperature of 80.3 °C, and the minimum volume is 0.99 ml at 40 °C. In the uniaxial loading stage, the maximum volume of gas desorbed is 0.90 ml at 80.7 °C, and the

| Serial number | Thermostatic temperature (°C) | Initial heating stage | Thermostatic stage | Uniaxial loading stage | Final heating stage |
|---------------|-------------------------------|-----------------------|--------------------|------------------------|---------------------|
| ZX1-1#        | 46.6                          | 1.01                  | 1.39               | 0.53                   | 7.58                |
| ZX1-2#        | 40.0                          | 0.25                  | 0.99               | 0.77                   | 2.37                |
| ZX2-1#        | 80.7                          | 1.64                  | 3.28               | 0.90                   | —                   |
| ZX2-3#        | 71.0                          | 1.39                  | 1.62               | 0.68                   | —                   |

Figure 12: SEM image of microstructure of the vicinity of macrocrack within posttest coal sample ZX1-1# and ZX1-2#. (The resolutions of (a) and (b) are 50 μm and 20 μm, respectively).
minimum value is 0.53 ml at 46°C. The desorption volume in the uniaxial stage is mainly affected not only by the temperature but also by the pressure. The new crack volume generated inside the coal sample under the action of pressure is also related to the difference in the size of the crack volume due to the difference in the nature of the specimen itself. For ZX1-1# and ZX1-2#, there is also a final heating stage, and it can be seen that the amount of gas desorbed from the coal sample is much larger than the other three stages in the case of final heating after the destruction and failure of the specimen. It indicates that the destruction of the specimen leads to the expansion and sprouting of new cracks, which greatly increases the rate of desorption and transport of adsorbed gas inside the coal sample.

Table 3 gives the average variation of gas concentrations at each stage. It can be seen that the concentration of CO2 in the four coal samples is always greater than the concentration of methane in all stages. In the initial heating stage, ZX1-2# corresponds to the largest CO2 component concentration with a value of 1.62%, ZX2-3# corresponds to the smallest CO2 component concentration with a value of 0.55%, and the CH4 concentration is generally less than 0.01%. In the thermostatic stage, ZX2-1# corresponds to the largest CO2 and CH4 component concentrations with values of 8.72% and 0.078%, respectively, while ZX2-3# corresponds to the smallest CO2 and CH4 concentrations with values of 0.907% and 0.003%. In the uniaxial loading phase, ZX2-1# corresponds to the largest CO2 and CH4 concentrations with values of 23.53% and 0.12%, respectively, while ZX1-1# corresponds to the smallest CO2 concentration with a value of 1.04% and ZX1-2# corresponding to the largest CO2 concentration with a value of 8.72%.

4. Conclusion

The adsorbed gas in coal is the basic source of gas, and its quantity is much higher than the quantity of free gas. Meanwhile, in the deep environment, the gas-bearing coal is not only affected by high temperature but also by high pressure, especially the presence of high pressure makes the coal body form cracks, and these cracks become the transport channels for desorbed gas. In this paper, the desorption and transport processes of adsorbed gas in four coal samples from Zhangxiaolou mine under the coupling of temperature and pressure are studied, and the changes of gas flow rate, pressure of emitted gas, and concentration of components during the desorption and diffusion of adsorbed gas are summarized. The following conclusions were reached:

(1) The desorption and diffusion characteristics of adsorbed gas under the coupling effect of temperature and pressure were measured by using the deep coal sample adsorption gas test system on coal samples from Zhangxiaolou mine. The gas desorption volume, escape pressure, and component concentration of the desorbed gas were also analyzed.

(2) Experiments confirm that the desorption rate of gas adsorbed in coal increases with the increase of temperature. The increase of temperature expands the matrix of coal rock, increases the internal pore pressure, and increases the kinetic energy of gas; therefore, the gas in the high-pressure area inside the coal rock flows to the low-pressure area. Some of the gases diffuse to the outside of the coal sample, forming a positive escape gas pressure. Due to the uncertainty of the internal high-pressure zone, the escape gas pressure shows a large alternating positive and negative change.

(3) The experiments reproduce the phenomenon that the pressure of the emitted gas suddenly becomes negative at uniaxial loading stage. The relationship between the fracture growth process and the desorption and transport of the adsorbed gas is described. The emergence of fracture cracking implies the appearance of negative escape gas pressure, and the two are essentially synchronized. The negative gas pressure is maximized at the time when the peak stress is reached in the coal sample. When the pressure is relieved, new desorbed gas continuously fills the negative pressure space until the positive gas...
pressure appears, and the appearance of positive gas pressure is found to be hysteresis. And the reasons for its occurrence were analyzed by SEM images before and after the experiment.

**Data Availability**

The data are available and explained in this article, and readers can access the data supporting the conclusions of this study.

**Conflicts of Interest**

No conflict of interest exists in the submission of this manuscript.

**Authors’ Contributions**

The manuscript is approved by all authors for publication.

**Acknowledgments**

This work was supported by the Technology Top Talent Support Project of the Department of Education of Guizhou Province (2020155), the Research and Development Project of Guizhou University of Engineering Science (Grant No. G2018016), the Bijie City Science and Technology Plan Joint Fund Project (201926), and the open research fund no. G2018016), the Bijie City Science and Technology Plan Support Project of the Department of Education of Guizhou Province (2020155), the Research and Development Projects of the Ministry of Science and Technology.

**References**

[1] H. Manchao, X. Heping, P. Suping, and J. Yaodong, “Study on rock mechanics in deep mining engineering,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 24, no. 16, pp. 2803–2813, 2005.

[2] W. Yu, J. Liu, D. Elsworth, H. Siriwardane, and X. Miao, “Evolution of coal permeability: contribution of heterogeneous swelling processes,” *International Journal of Coal Geology*, vol. 88, no. 2-3, pp. 152–162, 2011.

[3] W. H. Somerton, I. M. Soylemezoglu, and R. C. Dudley, “Effect of stress on permeability of coal,” *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 12, no. 5-6, pp. 129–145, 1975.

[4] Q. Wang, M. C. He, S. C. Li et al., “Comparative study of model tests on automatically formed roadway and gob-side entry driving in deep coal mines,” *International Journal of Mining Science and Technology*, vol. 31, no. 4, pp. 591–601, 2021.

[5] S. Durucan and J. S. Edwards, “The effects of stress and fracturing on permeability of coal,” *Mining Science and Technology*, vol. 3, no. 3, pp. 205–216, 1986.

[6] P. Q. Huy, K. Sasaki, Y. Sugai, and S. Ichikawa, “Carbon dioxide gas permeability of coal core samples and estimation of fracture aperture width,” *International Journal of Coal Geology*, vol. 83, no. 1, pp. 1–10, 2010.

[7] S. Mazumder and K. H. Wolf, “Differential swelling and permeability change of coal in response to CO2 injection for ECBM,” *International Journal of Coal Geology*, vol. 74, no. 2, pp. 123–138, 2008.

[8] M. Z. Gao, J. Xie, J. Guo, Y. Q. Lu, Z. Q. He, and C. Li, “Fractal evolution and connectivity characteristics of mining-induced crack networks in coal masses at different depths,” *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, vol. 7, no. 1, article 9, 2021.

[9] M. Z. Gao, J. Xie, Y. N. Gao et al., “Mechanical behavior of coal under different mining rates: A case study from laboratory experiments to field testing,” *International Journal of Mining Science and Technology*, vol. 31, pp. 825–841, 2021.

[10] E. P. Robertson and R. L. Christiansen, “Measurement of Sorption Induced Strain,” in *Paper 0532, Proceedings of the 2005 International Coalbed Methane Symposium*, Tuscaloosa, AL, 2005.

[11] G. X. Wang, P. Massarotto, and V. Rudolph, “An improved permeability model of coal for coalbed methane recovery and CO2 geosequestration,” *International Journal of Coal Geology*, vol. 77, no. 1-2, pp. 127–136, 2009.

[12] H. Siriwardane, I. Haljasmaa, R. McLendon, G. Irdi, Y. Soong, and G. Bromhal, “Influence of carbon dioxide on coal permeability determined by pressure transient methods,” *International Journal of Coal Geology*, vol. 77, no. 1-2, pp. 109–118, 2009.

[13] F. Han, A. Busch, N. van Wageningen, J. Yang, Z. Liu, and B. M. Krooss, “Experimental study of gas and water transport processes in the inter-cleat (matrix) system of coal: anthracite from Qinshui Basin, China,” *International Journal of Coal Geology*, vol. 81, no. 2, pp. 128–138, 2010.

[14] C. Zhu, K. Zhang, H. Cai et al., “Combined application of optical fibers and CRLD bolts to monitor deformation of a pit-in-pit foundation,” *Advances in Civil Engineering*, vol. 2019, Article ID 2572034, 16 pages, 2019.

[15] M. Bai and D. Elsworth, *Coupled Processes in Subsurface Deformation, Flow and Transport*, ASCE Press, 2000.

[16] V. N. Romanov, A. L. Goodman, and J. W. Larsen, “Errors in CO2 Adsorption Measurements caused by coal Swelling,” *Energy and Fuels*, vol. 20, no. 1, pp. 415–416, 2006.

[17] Y.-c. Deng, H.-p. Xie, R.-q. Huang, and C.-q. Liu, “Law of gas nonlinear flow in low permeability pore-fissure media,” *Journal of Sichuan University (Engineering Science Edition)*, vol. 38, no. 4, pp. 1–4, 2006.

[18] T. Zhigang, Z. Chun, W. Yong, W. Jiamin, H. Manchao, and Z. Bo, “Research on stability of an open-pit mine dump with fiber optic monitoring,” *Geofluids*, vol. 2018, Article ID 9631706, 20 pages, 2018.

[19] Z. Jianxun, G. Wang, and S. Zhenjie, “Coal deformation under high temperature and confining pressure,” *Journal of China Coal Society*, vol. 19, no. 3, pp. 324–332, 1994.

[20] J. Gawuga, *Flow of gas through stressed carboniferous strata*, [Ph.D. thesis], University of Nottingham, 1979.

[21] V. V. Khodot, “Role of methane in the stress state of a coal seam,” *Journal of Mining Science*, vol. 16, no. 5, pp. 460–466, 1980.

[22] X. S. Li, K. Peng, J. Peng, and D. Hou, “Experimental investigation of cyclic wetting-drying effect on mechanical behavior of a medium-grained sandstone,” *Engineering Geology*, vol. 293, article 106335, 2021.

[23] S. Harpalani, *Gas flow through stressed coal*, [Ph.D. thesis], University of California Berkeley, 1985.

[24] K. Winter and H. Janas, “Gas emission characteristics of coal and methods of determining the desorbable gas content by means of desorbometers,” in *XIV International Conference of*
Coal Mine Safety Research, Washington, D. C., September 1975.

[25] E. M. Airey, "Gas emission from broken coal. An experimental and theoretical investigation," *International Journal of Rock Mechanics and Mineral Sciences*, vol. 5, no. 6, pp. 475–494, 1968.

[26] Y.-a. Wang and S.-j. Yang, "Some characteristics of coal seams with hazard of outburst," *Journal of China Coal Society*, vol. 1, no. 6, 1980.

[27] X. S. Li, K. Peng, J. Peng, and H. Xu, "Effect of cyclic wetting-drying treatment on strength and failure behavior of two quartz-rich sandstones under direct shear," *Rock Mechanics and Rock Engineering*, vol. 6, 2021.

[28] M. C. He, C. G. Wang, J. L. Feng, D. J. Li, and G. Y. Zhang, "Experimental investigations on gas desorption and transport in stressed coal under isothermal conditions," *International Journal of Coal Geology*, vol. 83, no. 4, pp. 377–386, 2010.

[29] X. Zhang, H. Li, C. Wang, Z. Zhao, L. Li, and X. Wang, "Experimental and numerical simulation of desorption and diffusion process of the adsorbed gas in coal rock under isothermal conditions," *Geo Fluids*, vol. 2021, Article ID 6672424, 15 pages, 2021.

[30] M. Cai, "Influence of intermediate principal stress on rock fracturing and strength near excavation boundaries—Insight from numerical modeling," *International Journal of Rock Mechanics and Mining Sciences*, vol. 45, no. 5, pp. 763–772, 2008.

[31] F. Wu, H. Zhang, Q. L. Zou, C. B. Li, J. Chen, and R. B. Gao, "Viscoelastic-plastic damage creep model for salt rock based on fractional derivative theory," *Mechanics of Materials*, vol. 150, article 103600, 2020.

[32] C. Wang, J. Zhang, Y. Zhang et al., "Time-dependent coal permeability: Impact of gas transport from coal cleats to matrices," *Journal of Natural Gas Science and Engineering*, vol. 88, article 103806, 2021.

[33] P. Liu, Y. Qin, S. Liu, and Y. Hao, "Non-linear gas desorption and transport behavior in coal matrix: experiments and numerical modeling," *Fuel*, vol. 214, pp. 1–13, 2018.

[34] Y. Wu, L. Cheng, L. Ma et al., "A transient two-phase flow model for production prediction of tight gas wells with fracturing fluid-induced formation damage," *Journal of Petroleum Science and Engineering*, vol. 199, article 108351, 2021.

[35] Y. Wang, B. Zhang, B. Li, and C. H. Li, "A strain-based fatigue damage model for naturally fractured marble subjected to freeze-thaw and uniaxial cyclic loads," *International Journal of Damage Mechanics*, vol. 30, no. 9, 2021.

[36] H. Wu, D. Ma, and A. J. S. Spearing, "Fracture phenomena and mechanisms of brittle rock with different numbers of openings under uniaxial loading," *Geomechanics and Engineering*, vol. 25, no. 6, pp. 481–493, 2021.

[37] X. Zhang, Y. Chang, and X. Ren, "Gas desorption and transportation in original coal of Baijiao Coal Mine under temperature-stress loading condition," in *2015 joint international mechanical, Electronic and Information Technology Conference*, Chongqing, December 2015.

[38] K. Jin, Y. Cheng, T. Ren et al., "Experimental investigation on the formation and transport mechanism of outburst coal-gas flow: implications for the role of gas desorption in the development stage of outburst," *International Journal of Coal Geology*, vol. 194, pp. 45–58, 2018.