Research Article

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Study on the law of coal resistivity variation in the process of gas adsorption/desorption

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Abstract: In order to detect coal and gas outburst disasters by means of electric exploration technology, the characteristics of gas adsorption/desorption electrical response were studied. The law of resistivity variation of different coal samples was investigated under different gas pressures with the aid of a self-built real-time test system of coal resistivity during gas adsorption/desorption. In addition, the mechanism of coal resistivity variation was studied. The research results indicate that coal resistivity decreases during gas adsorption and increases during gas desorption, but generally it cannot return to the initial value. Gas influences coal resistivity through a variety of mechanisms. In the gas adsorption process, coal resistivity decreases under the combined effect of surface energy decline, skeleton expansion, free gas pressure and adsorption swelling stress. In addition, as the gas pressure rises, the resistivity varies in a wider range. The coal resistivity shares the relation of $y = a + b \ln(x + c)$ with gas pressure and the relation of $y = ax + b$ with the content of adsorbed gas. This study lays a foundation for the application of electrical prospecting technology to gas hazard prediction and provides technical support for safe production in coal mines.

Keywords: Resistivity, Adsorption/desorption, Gas pressure, Action mechanism

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1 Introduction

In China, 90% of coal mines are underground mines where gas is called the “first killer” for safe production. With the increase in energy demand, coal mines in China have successively entered deep mining. In the high-stress and high-gas complex environment, coal and gas outburst disasters are becoming increasingly serious, which has significantly restricted the safe production of mines [1]. Gas outburst disasters have become a key factor restricting the efficient production of some large coal mining companies. Therefore, the management of gas in coal mines, especially the control of coal and gas outburst disasters, has always been one of the technical issues of most concern in China’s coal industry [2, 3].

Gas is mainly deposited in coal seams as adsorbed gas, free gas and dissolved gas, among which adsorbed gas accounts for over 80%-90% [4]. Gas adsorption on coal is a key factor affecting gas content in coal seams [5]. Gas outburst disasters are often accompanied by a large amount of gas emission and ejection, which is essentially the intense gas desorption from coal seams [6]. Therefore, gas adsorption/desorption has always been a hot topic of research [7, 8]. It has important theoretical and practical significance for coal and gas outburst prediction, study of the coal bed methane (CBM) flow mechanism and CBM extraction and utilization.

Based on the difference in electrical properties of the medium, electrical exploration is a geophysical exploration method for detecting geological anomalies by observing and analyzing the law of electric field distribution variation. It has been widely used for detecting underground structures, water-bearing areas, fracture zones, etc. [9–11]. The evolution of gas disasters is accompanied by multiple physical and mechanical responses [12]. Resistivity is one of the important electrical parameters, and it is also the physical premise for electrical exploration in coal mines [13]. The coal seam gas pressure is positively correlated with the gas content. These two factors jointly determine the outburst danger of the coal seam. Especially in the local area, the coal seam gas easily accumulates. This situation is very dangerous in the mining process, and it can easily cause coal and gas outbursts. But, the current detection technology and equipment are still immature. There are also some disaster phenomena related to gas desorption in coal, such as large-scale coal gangs, gas injection during drilling holes, and coal body extrusion with a large amount of gas pouring out, etc. There is currently no effective means for monitoring and early warning. The study of the coal resistivity during gas adsorption/desorption aims to understand the difference in coal electrical properties caused by gas adsorption/desorption behavior and is of great significance for the application of an electric method exploration technology for gas disaster prediction.

The process of gas adsorption/desorption is accompanied by gas diffusion and seepage [14], the deformation of the coal skeleton, etc. [15]. This results from the interaction between adsorbed gas and free gas. The presence of gas will change the electrical resistivity of coal. Xu *et al.* [16] carried out a gas filling experiment on anthracite from the Baijiao Coal Mine in Sichuan Province, China, and tested the coal resistivity after the gas adsorption equilibrium was reached. It was found that the coal resistivity decreased with the rise of gas pressure in both direct electric field and an alternating electric field. In addition, the resistivity obtained in the test exhibited fractal characteristics. Wen *et al.* [17] performed 45 measurements on the resistivity of 7 coal samples taken from different sites in the gas pressure range of 0-6 MPa. Moreover, they fitted the coal resistivity and the adsorbed gas pressure, revealing that the resistivity of 4 coal samples decreased with the rise of adsorbed gas pressure, which is consistent with the change law described by Xu *et al.* [16], and the resistivity of the other 3 coal samples increased with the rise of adsorbed gas pressure. Yang *et al.* [18] conducted gas adsorption experiments on briquette coal and raw coal from different mining areas, and tested the law of resistivity variation in the gas adsorption process under 0.8 MPa of gas pressure. The results suggested that the resistivity of bituminous coal and anthracite coal both exhibited downward trends in the gas-containing environment. Chen *et al.* [19] carried out a gas-containing coal extrusion test, which is a coal gas desorption process, including coal body loading, gas filling, and sudden pressure relief. In this way, the law of resistivity change is obtained.

Previous studies mostly focused on the overall relationship between adsorbed gas pressure and coal resistivity and failed to achieve continuous real-time testing of coal resistivity during gas adsorption/desorption. The characteristics of resistivity variation caused by gas desorption has not been studied, and the mechanism for resistivity variation caused by gas needs further research. In this paper, the real-time test system of coal resistivity during gas adsorption/desorption was established to test and analyze the variation law and mechanism of different coal samples under different gas pressures. The study lays a foundation for the prediction of gas disasters by means of an electric exploration technology and improves application and development of coalfield geophysical exploration technology.

2 Experimental method

2.1 Experimental system

The experimental system includes a resistivity test system, a sealed cylinder, a high-pressure gas source, a piping system, a valve, a pressure gauge, and a vacuum pump (Figure 1). The resistivity test system adopts the Agilent U1733C LCR meter which can continuously acquire data through its own software when connected to a PC. The experimental coal samples were taken from different mining areas, and the basic conditions are shown in Table 1. The large pieces of coal were processed into Φ50 mm×100 mm cylinders with a core tube and had the two ends ground flat. After the standard samples were prepared, they were placed in a drying oven to remove the moisture. Conductive paste was applied between the copper electrode and the end face, and the sample was connected to the LCR meter with an enameled wire.

In this study, with CH_4 taken as the experimental gas, the adsorption/desorption experiments were performed under gas pressures of 0.5 MPa, 1.0 MPa, and 1.5 MPa, and the coal samples were allowed to adsorb gas under constant pressures during the experiment. Upon the completion of the experiment at each pressure level, a fresh coal sample was used for the experiment at the next pressure level. The coal resistivity was continuously tested during the experiment. The sealed cylinder was placed in a 25°C constant temperature water bath whose temperature was in line with the underground environmental temperature.

3 Analysis of experimental results

According to the working principle of the LCR meter, the measured resistance value is converted into a resistivity value by Eqs. (1) and (2):

$$R = |Z| \cos\theta \tag{1}$$

$$\rho = |Z| \cos\theta \cdot S/L = RS/L \tag{2}$$

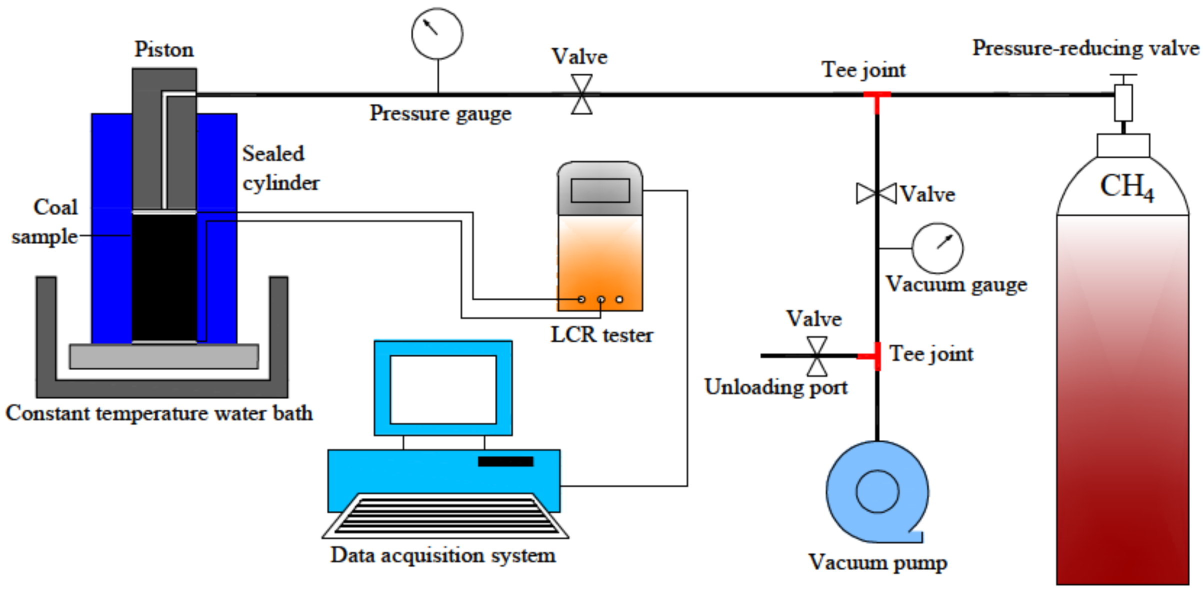

Figure 1: Schematic diagram of experimental system

Table 1: Basic information of experimental coal samples

Coal sample source	Coal seam number	Mining area	Sampling location	Buried depth/m	Original resistivity range/Ω·m
Chengjiao Mine	No. 2 coal in the 2nd seam	Yongxia Mining Area	−750 downward roadway	785	1563.14-2667.27
Xing'an Mine	No. 17 coal	Hegang Mining Area	1701 mining face	676	465.17-754.93
Sijiazhuang Mine	No. 15 coal	Yangquan Mining Area	15104 return airway	605	756.43-956.54
Zhuxianzhuang Mine	No. 8 coal	Huaibei Mining Area	874 air-returning stone gate	420	85.32-112.35
Xinji No.2 Mine	No. 4 coal	Huainan Mining Area	−550 m west alley	576	690.58-895.43

where Z is the impedance value (Ω); θ is the phase angle (°); ρ is the resistivity (Ωm); R is resistance (Ω); S is the cross-sectional area of sample (m^2); and L is the sample length (m). In order to facilitate the study of the law of resistivity variation, the parameter λ is introduced to represent the magnitude of resistivity variation:

$$\lambda = \rho/\rho_0 \tag{3}$$

where ρ is the measured resistivity, Ωm; and ρ_0 is the initial resistivity, Ωm.

When $\lambda > 1$, the larger the λ is, the more significantly the resistivity increases. When $\lambda < 1$, the smaller the λ is, the more significantly the resistivity decreases.

The presence of gas changes the environment where the coal occurs, further altering the state of the coal. During gas adsorption and desorption, coal resistivity changes significantly. The diagram of λ variation (Figure 2) reveals the law of resistivity variation:

(1) Although the coal samples are taken from different mining areas, they have a consistent trend in the gas adsorption and desorption process, *i.e.*, the resistivity decreases during the adsorption phase and increases during the desorption phase. The resistivity always shows the opposite trends in the two phases.
(2) For all the five experimental samples, the λ curves increase from 0.5 MPa through 1.0 MPa to 1.5 MPa, which indicates that the resistivity varies in a greater range with an increase of gas pressure.
(3) The initial moments of gas adsorption and desorption are often accompanied by a sudden rise of coal

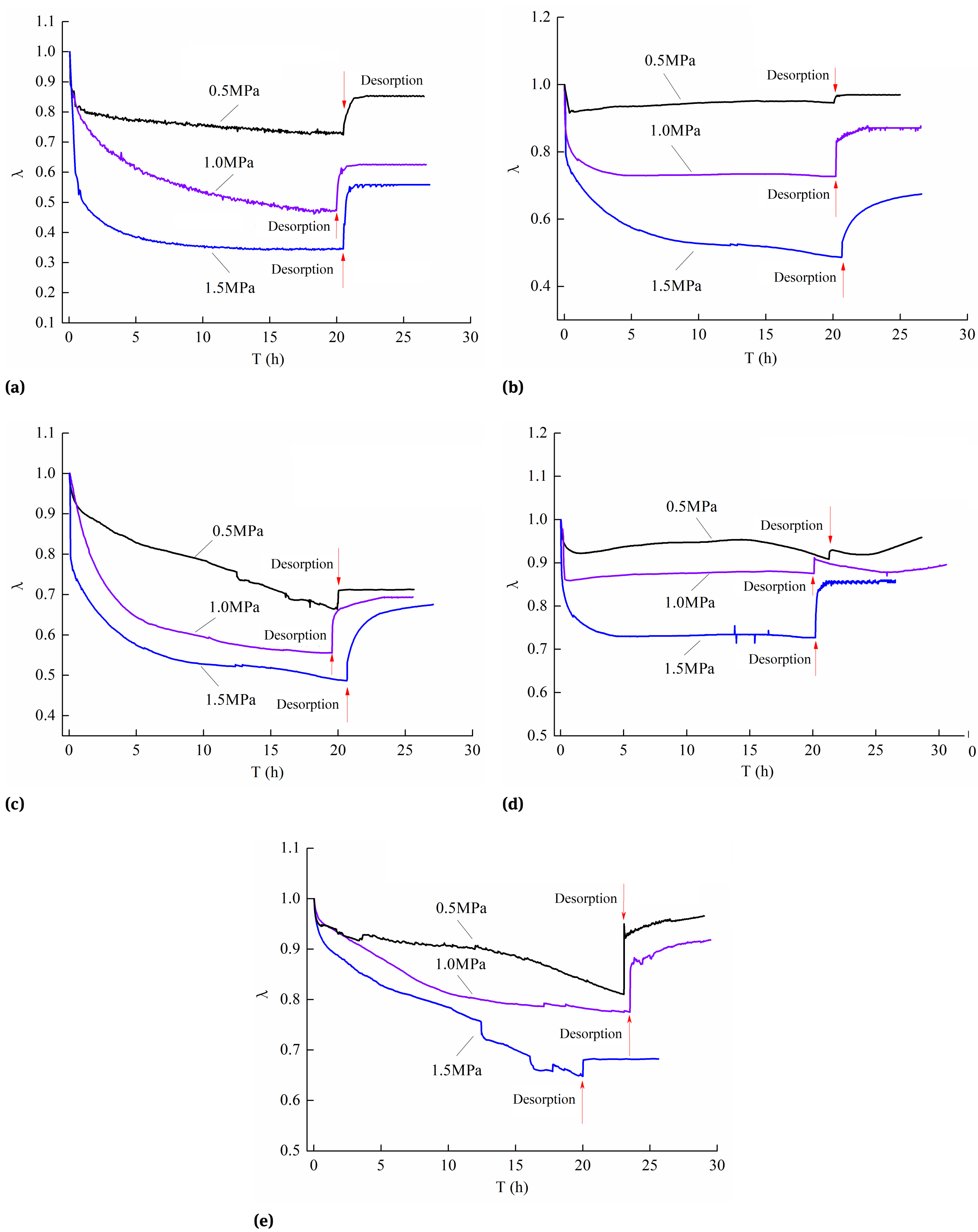

Figure 2: Diagram of λ variation the CH_4 adsorption/desorption process. a) Chengjiao coal sample and b) Xing'an coal sample, c) Sijiazhuang coal sample and d) Zhuxianzhuang coal sample, e) Xinji No. 2 coal sample

Table 2: Fitting results of λ with *P* and *W*

Coal sample source	*P-λ* fitting formula	Correlation coefficient R^2	Adsorption constant $a/(m^3/t)$	Adsorption constant b/MPa^{-1}	*W-λ* fitting formula	Correlation coefficient R^2
Chengjiao Mine	y=0.85453-0.38242ln(x+0.59758)	0.99921	15.9639	0.4595	y=1.0342-0.071x	0.99954
Xing'an Mine	y=0.7745-0.2510ln(x+0.2612)	0.97761	17.9367	1.1034	y=1.119-0.04x	0.98424
Sijiazhuang Mine	y=0.64491-0.28336ln(x-0.21197)	0.98955	33.1747	1.3451	y=1.104-0.02x	0.98906
Zhuxianzhuang Mine	y=1.3432-0.3902ln(x+2.3717)	0.99128	21.3521	0.6261	y=1.03859-0.02198x	0.97217
Xinji No.2 Mine	y=1.0033-0.3158ln(x+0.9740)	0.96958	22.3894	0.9435	y=1.0638-0.0266x	0.95700

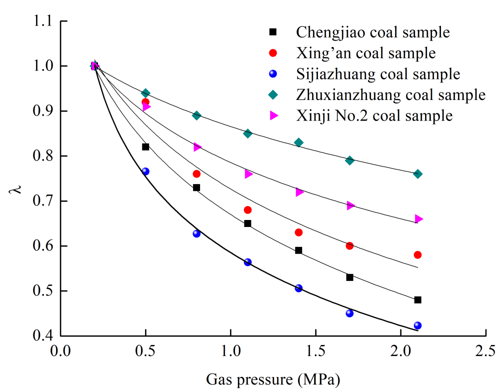

Figure 3: The fitting curve of λ with P

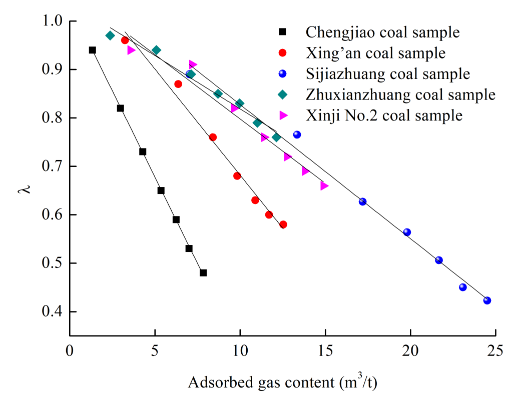

Figure 4: The fitting curve of λ with W

resistivity. Although λ approaches the initial value 1, it does not return to 1.

(4) Due to the difference between coal samples, the forms of the λ curves differ, with some being relatively smooth (such as the Xing'an coal sample) and some being more volatile (such as the Xinji No. 2 coal sample). The reduction ranges of resistivity at the moment of adsorption equilibrium differ. Taking the 1.5 MPa curve of each experimental sample as an example, the resistivity of Chengjiao coal undergoes the largest decline ($\lambda = 0.35$), and the resistivity of Zhuxianzhuang coal decreases the least ($\lambda = 0.72$).

In order to quantitatively investigate the relationship between the coal resistivity and the gas pressure, a specific pressure of gas was injected into each sample, and the resistivity value was recorded after the adsorption equilibrium was reached. Then, the pressure was increased continuously, and the resistivity value was recorded at the adsorption equilibrium. In this way, the relationship between gas pressure and coal resistivity was obtained [20–22]. The fitting between the two demonstrates that the coal resistivity varies in accordance with the logarithmic function $y = a + b\ln(x + c)$ with the change of gas pressure P (Figure 3), especially the initial stage of the test. In the later stage, the change in resistivity slows down as the gas pressure rises, because the coal sample gradually approaches the adsorption limit. Gas presents within the coal mainly in the adsorption state. The adsorbed gas content W under different gas pressures in Figure 3 can be calculated according to the Langmuir equation $x = \frac{abp}{1+bp}$. The fitting between W and λ shows that the resistivity of 5 coal samples and the adsorbed gas content W share a linear relationship $y = ax + b$ (Figure 4). The fitting results of λ with *P* and *W* are shown in Table 2.

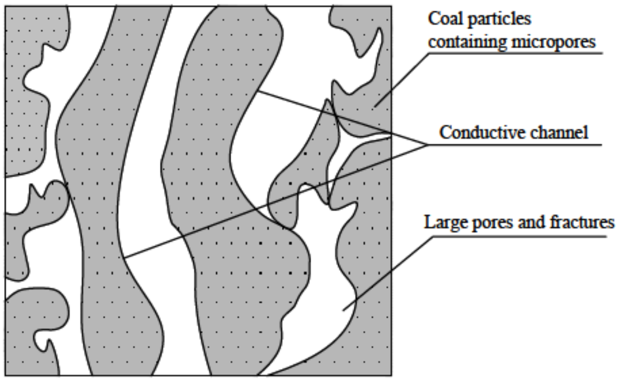

Figure 5: Diagram of coal conductive channel

4 Discussion

Coal is a kind of medium with pores and fractures. Under the action of an external electric field, the pores and fractures can be regarded as insulators which do not participate in conduction. Only the coal matrix can conduct current, and the coal matrix is called the conductive channel (Figure 5). Under the influence of an external environment, the change in coal resistivity essentially depends on the changes in physical and mechanical characteristics of the conductive channel [23].

Therefore, the influence mechanism of gas on coal resistivity in the adsorption process can be analyzed from the following four aspects:

(1) Since the adsorption is an exothermic process, the adsorption heat released by the coal reduces the surface energy of the pores, thereby weakening the binding effect of surface hetero ions and surface electrons. As a result, hetero ions and electrons migrate more easily on the pore surface, which leads to an enhancement of conductivity and a decrease in resistivity.
(2) Methane molecules penetrate into the macromolecular gap of coal, causing a certain expansion of the skeleton. The higher the gas pressure in coal, the larger the expansion effect, and the weaker the interaction between molecules. Hence, the conductive energy barrier and the resistivity both decrease.
(3) Free gas with a certain pressure has a squeezing effect on the coal particles. The higher the gas pressure, the stronger the pressing effect. The higher gas pressure raises the external pressure on the conductive channel, which is similar to the effect of stress on coal.
(4) The conductivity of coal is mainly due to ion conduction and electronic conduction. As a solid conductive medium, all types of coal are electronically conductive, and most coal is primarily electronically conductive. Under the action of stress, the electron clouds between molecules of solids overlap, and the electrons become more mobile between the molecules, inducing an increase of electron conductivity and a drop of electron resistivity [24]. Therefore, the squeeze of free gas lowers the resistivity.
(5) Adsorption expansion stress is produced during gas adsorption on coal. Under higher gas pressure, the expansion stress is greater [25], so is the supporting force between coal particles. Accordingly, the squeeze on coal particles is stronger. Since the conductive channels in coal are composed of numerous micropore-containing coal particles, the microscopic squeeze on coal particles is reflected by the squeeze on conductive channels in coal macroscopically. This effect, which is consistent with the effect described in Aspect (3), will also lower the resistivity of coal [26].

The higher the gas pressure is, the larger the adsorbed gas content is. Accordingly, the effects of the above four aspects are stronger, and the range of resistivity variation is greater.

At the initial moments of gas adsorption and desorption, the resistivity decreases and increases suddenly due to sudden changes in the environment where the coal exists. In the desorption process, the adsorbed gas turns free and desorbs from the adsorption system, resulting in a decrease in the adsorbed gas content as well as a volume shrinkage. After the gas suddenly desorbs from coal, a series of behaviors opposite to the adsorption process occur within the coal, *i.e.*, after the coal absorbs heat, the surface energy increases, and the coal skeleton shrinks. Meanwhile, the free gas pressure and the adsorption expansion stress are released. Thus, the resistivity curve of the desorption phase is opposite to that of the adsorption phase. Desorption is a process in which the coal recovers its original state before adsorption. Nevertheless, it is found through experiments that after a certain period of desorption, the coal resistivity cannot be restored to the initial value, because of some irreversible deformation of the coal. Although gas adsorption on coal belongs to physical adsorption, the deformation which occurs in the desorption process cannot happen along the original trajectory of the adsorption process. The rapid unloading of confining pressure generated by the gas around the coal quickly closes the micropores and microcracks and restricts the gas migration channel. Hence, the gas that originally entered the coal matrix under gas pressure cannot be released. This is why some irreversible deformation always exists.

In the actual environment of coal mines, the methane adsorbed in coal has reached a stable equilibrium state after a long term of geological evolution. Then, mining activities in the underground roadway break the original stress balance and thus break the adsorption equilibrium state. In this way, gas molecules can get rid of the adsorption force on the inner surface of pores. Then, they will transform from the adsorption state to the free state and flow into the working surface or the roadway. When the gas enrichment area is suddenly exposed, a large amount of high-pressure gas suddenly desorbs and breaks the resistance of the coal pillar, leading to coal and gas outburst disasters. Therefore, when the electrical method is adopted to monitor coal and gas outbursts, special attention should be paid to the sudden change in resistivity.

According to the characteristics of gas absorption/desorption, the downhole area can be detected and different gas pressure states can be reversed to detect the danger of coal and gas outbursts. The gas depletion characteristics can also be monitored according to the desorption characteristics. Therefore, the electric exploration technology provides an effective technical means for the prevention and control of coal and gas outburst disasters, and is of great significance for promoting safe production in coal mines.

5 Conclusions

(1) In the gas adsorption process, the coal resistivity falls under the combined action of surface energy decline, skeleton expansion, free gas pressure and adsorption swelling stress.

(2) At the moment of gas adsorption equilibrium, the range of coal resistivity variation is related to gas pressure. As the gas pressure increases, the change in resistivity increases. The coal resistivity shares a logarithmic function relationship $y = a + b\ln(x + c)$ with gas pressure and a linear function relationship $y = ax + b$ with the adsorbed gas content.

(3) The law of coal resistivity variation in the gas desorption phase is always opposite to that in the adsorption phase, and initial moments of both phases are accompanied by a sudden change in resistivity. The coal resistivity after desorption cannot return to the initial value, because of some of irreversible deformation of the coal.

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