EXPERIMENTAL STUDY ON RESISTIVITY RESPONSE CHARACTERISTICS OF LOADED COAL DURING NITROGEN INJECTION

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In order to explore the evolution of coal cracks during nitrogen injection, the resistivity response tests of coal during nitrogen injection were carried out. The research shows that during the nitrogen injection process, the resistivity of the coal remains basically unchanged at first, then increases slowly, and increases suddenly and stabilizes at about 1.2finally. The nitrogenadsorption ofcoal leads to a decrease in resistivity, and the higher the nitrogen pressure is, the greater the decrease in resistivity will be. The development of fissures in the coal will affect the conduction channel, resulting in an increase in resistivity. In the process of nitrogen injection, the resistivity change of the loaded coal is the result of the combined effect of the nitrogen adsorption of coal and the expansion of the fissures of the coal.

Key words: *Permeability enhancements of coal seam; nitrogen injection; resistivity; axial compression; crack initiation pressure*

Introduction

The geological conditions of coal mines in China are complex, the permeability of more than 70% of coal seams is less than 1.0 mD, making coalbed methane extraction difficult [1]. With the reduction and depletion of shallow coal resources, the mining depth of coal mines in China increases at a rate of 8-12m/a (the fastest is nearly 50m/a), the gas pressure and content of coal seams will be greater, and the coal permeability will be lower continuously [2,3]. The low permeability of coal seams will seriously affect the effect of gas drainage, resulting in serious consequences such as difficulty in eliminating gas disasters and low utilization efficiency of coalbed methane resources. Therefore, coal seam permeability enhancement is the key togas dynamic disaster prevention in low permeability coal seams and

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the safe and efficient gas drainage. In recent years, many experts have explored and developed new technologies of waterless fracturing and permeability enhancement, one of which is the injection of nitrogen into the coal seam to fracture the coal [4].

In the process of coal fracture evolution, there are various physical and mechanical responses, and resistivity is one of the important parameters. Its difference reflects the development and expansion of cracks in the coal, and then reflects its state of destruction [5]. Liu *et al.* applied resistivity tomography in mine water inrush test [6]. Wang *et al.* studied the resistivity response law of the loaded coal during the full stress-strain process[7]. Ma et al. studied the corresponding characteristics of the resistivity during the hydraulic fracturing in coal [8]. Chen et al. studied the influence of coal on the change law of resistivity under different loading modes and gas adsorption[9]. Lyu *et al.* believed that the adsorption capacity of gas and electrical conductivity presented a power function relationship [10]. Li *et al.* analyzed the pore-fracture structure characteristics of coal samples and their influence on resistivity anisotropy [11]. Therefore, in order to better study the microscopic damage activities in the process of nitrogen fracturing coal, the American Agilent U1733C LCR tester was used to study the evolution characteristics of the resistivity of the loaded coal during nitrogen injection. The results are expected to guide the practicalapplication of nitrogen injections in coal mines.

Experiments

The test system of coal resistivity during nitrogen injection consists of loading system, nitrogen injection system and resistivity test system (fig.1). The loading system is a TAW-2000 mechanical servo-controlled testing machine with a maximum axial pressure of 2000kN, which is used to provide the required axial pressure for the test.Nitrogen injection system includes air compressor, refrigerating machine, air storage tank, control cabinet, booster pump and nitrogen bottle. It is used to test the crack initiation pressure of coal under nitrogen injection.The resistivity test system is mainly composed of LCR tester and computer.

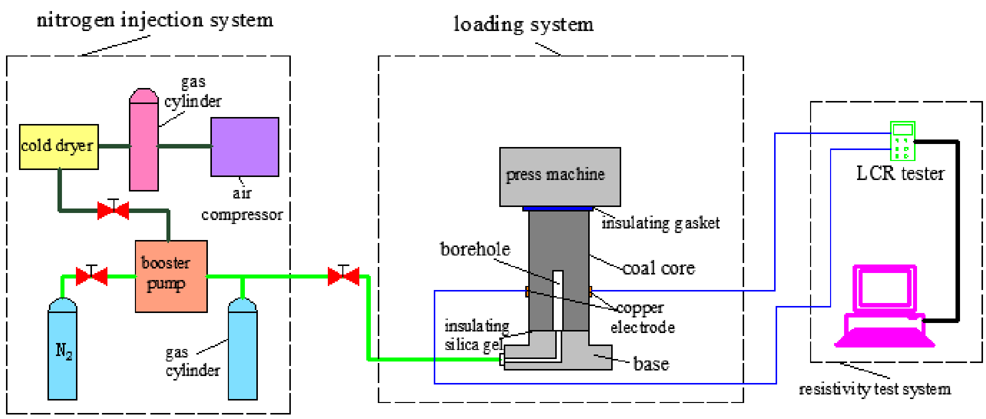

Figure 1. Coal resistivity test system during nitrogen injection

Studies have shown that, the frequency has a great influence on the resistivity.The higher the frequency is, the smaller the resistivity of the coal is [12]. 10kHz as the test frequency was selected, and this frequency is the commonly used test frequency.To express the change of resistivity, for the convenience of calculation, the measured resistance value is converted into the resistivity of the experimental sample [12]:

$$\rho = {R_m S}/{L_1} \tag{1}$$

where ρ is the resistivity of coal, R_m is the resistance of coal, S is the cross-sectional area of the coal sample, and L_1 is the length between the two measuring points. It have been reported that cross-sectional area and the length between the two measuring points can be computed in [13-17] if there are considered in the complex behavior.

Since the coal samples are all processed according to the standard and the measuring points are arranged the same, the resistivity change is [12]:

$$\lambda = {\rho}/{\rho_0} = {R_m}/{R_0} \tag{2}$$

where ρ_0 is the initial resistivity of the coal and R_0 is the initial resistance of the coal.

The test coal samples were selected from the Baijigou mining area in China. On the basis of the standard coal sample (diameter 50mm, height 100mm), a circular hole with a diameter of 8mm and a depth of 50mm was drilled in the center of one end of the test piece, as shown in fig.2. Existing studies show that the stress level values corresponding to dilatation point of each experimental coal sample can be determined which distributes between 66%and 87% of uniaxial compressive strength[13]. That is to say, when the pressure received by the coal is less than 66% of the uniaxial compressive strength, the coal will be continuously compressed, and the pore and fracture space of the coal is continuously reduced, resulting in a decrease in the permeability of the coal. The uniaxial compression experiment was carried out on the coal, and the stress-strain curve is shown in fig.3. In the curve,the slope of tangent at A deviates from curve and decreases gradually, denoting the deformation of coal transits from elasticdeformation into plastic deformation. At this moment, shear fracture of coal sample happened, indicating the state of specimenturns from volume compression to dilatation.Combining the existing research results and the stress-strain curve of the coal, when the axial pressure of the coal is less than 13.5MPa, the coal must be in a compressed state. Based on this, the axial pressures were set to be 4, 6 and 8 MPa respectively to simulate different permeability of coal.

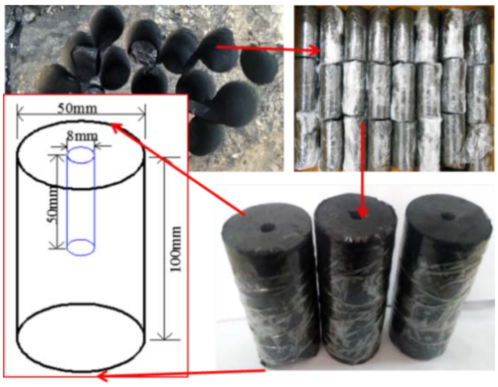

Figure 2. Coal sample

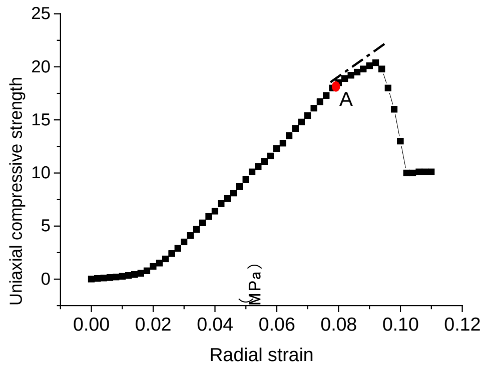

Figure 3.The stress-strain curves of coal

Response characteristics of resistivity in the process of nitrogen fracturing coal

The variation law of nitrogen pressure and resistivity under different axial pressure is shown in fig.4. It can be seen that the nitrogen pressure change is roughly divided into four stages, the equipment startup stage, the pressure rise stage, the pressure maintenance stage and the pressure decline stage. In the equipment startup stage, when the equipment operates normally and reaches the initial pressure of 0.1MPa, the three samples are almost indistinguishable. In the pressure rise stage, the pressure rise stage time corresponding to axial pressure of 4MPa, 6MPa and 8MPa is 82s, 45s and 44s respectively; under the condition of constant nitrogen flow, the longer the pressure rise stage is, the better the seepage effect of nitrogen in the coal becomes; the time of the pressure rise stage of the 6MPa and 8MPa axial pressures is almost the same, indicating that when the coal permeability is low to a certain extent, the coal seepage flow is very small in a short time. In the gas holding stage, the gas holding time corresponding to 4MPa, 6MPa and 8MPa axial pressure is 10s, 22s and 20s respectively; it shows that under the condition of low axial pressure (high permeability), gas diffusion is easy and coal is easy to be damaged, therefore the holding time is short. In the pressure decline stage, the time difference of the nitrogen pressure decline stage is almost the same, which means that after the coal is completely cracked, the gas is released rapidly and the gas pressure drops rapidly.As for thecoal resistivity, it remains almost unchanged at the initial moment of gas injection. With the passage of time, the nitrogen pressure rises and fluctuates, which is also the process of gas seepage and continuous pressure increase, and the resistivity increases slowly as well. When nitrogen pressure reaches the coal breaking pressure, the resistivity changes abruptly, the nitrogen pressure begins to drop, and the coal has been destroyed. After the coal is fractured, the resistivity remains relatively constant, all around 1.2. It can be seen from the photos of nitrogen-fractured coal under different axial pressures (fig.5) that the coal bodies are all split. The greater the axial pressure is, the greater the damage to the coal will be.

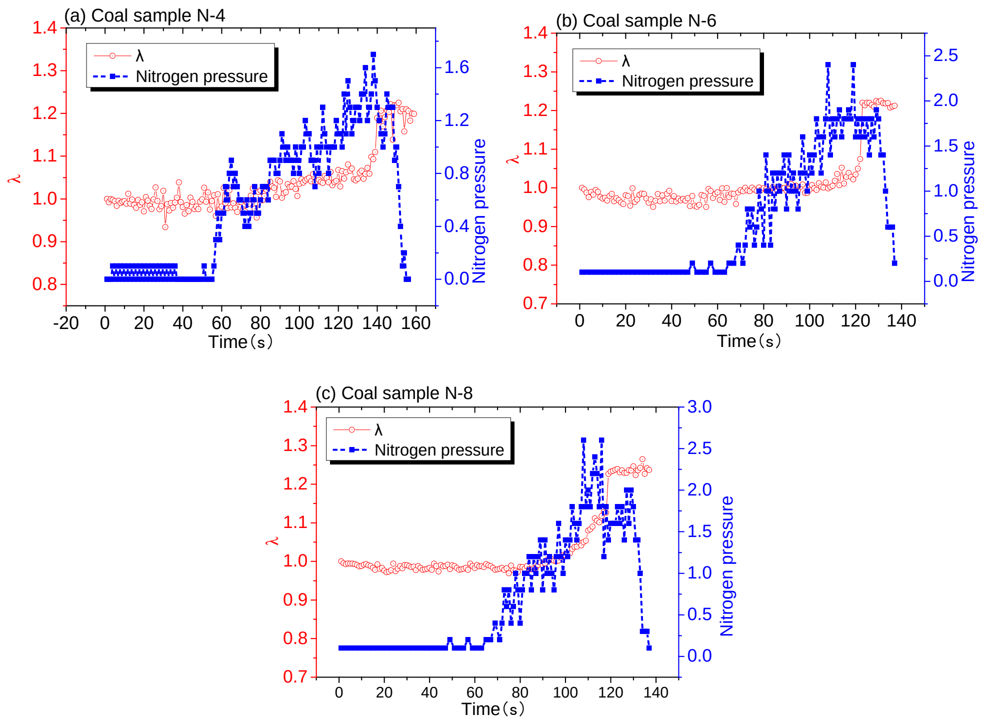

Figure 4. Nitrogen pressure and resistivity of different coal samples

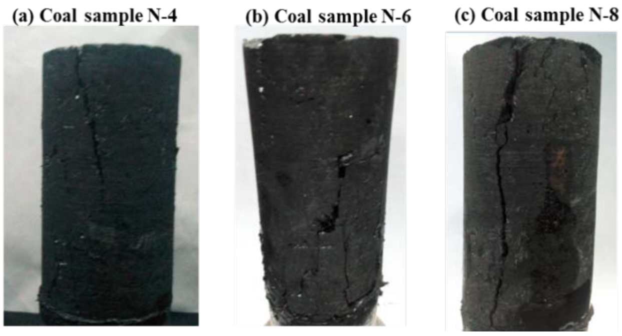

Figure 5. Splitting morphology of different coal samples

Influence of axial compression on nitrogen fracturing coal

The relationship among coal crack initiation pressure, time and axial pressure is shown in fig.6. It can be seen from the figure that the corresponding coal crack initiation pressure under the axial pressure of 4MPa, 6MPa and 8MPa is 1.7MPa, 2.4MPa and 2.6MPa respectively and the required crack initiation time is 138s, 119s and 116s, respectively. It reflects that the greater the axial pressure on coal is, the greater the crack initiation pressure is and the shorter the crack initiation time becomes. For coal samples under the action of uniaxial pressure, increasing the axial pressure will further compact the coal, and the permeability will decrease. In the process of nitrogen injection into the coal, for coal samples with high permeability, nitrogen can quickly seep to the surface of the test piece and then the pore pressure near the coal wall increases, which promotes the initiation of cracks in the coal wall. No confining pressure is applied during the nitrogen injection into the coal, so the fracture pressure is relatively small. For coal samples with low permeability (large axial pressure), nitrogen is easier to pressurize inside them, therefore the time required for fracturing is shorter.

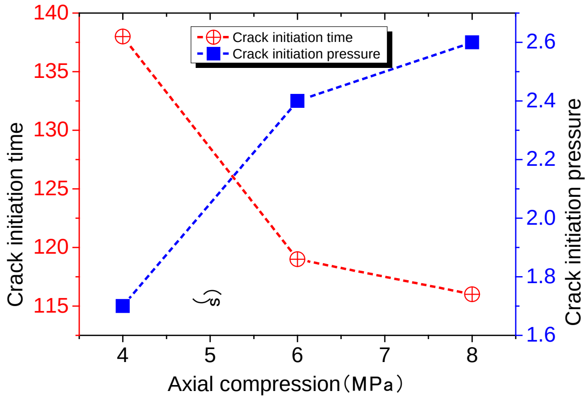

Figure 6. Initiation pressure and time during different axial compressions

Response mechanism of coal resistivity during nitrogen injection

The resistivity of coal is an important physical quantity reflecting the properties of coal. In this experiment, the coal is damaged under the action of nitrogen, and its resistivity change is mainly affected by nitrogen adsorption and the expansion of coal fissures.

Dry coal sample is used in this experiment, which is mainly electronically conductive, and the resistivity change mainly depends on the difficulty of electronic transition.

The research shows that the resistivity decreases in the adsorption stage, and the higher the nitrogen pressure is, the greater the resistivity declines; in the nitrogen desorption stage, the resistivity jumps upwards and then returns to the normal state. These phenomena reflect the influence of nitrogen adsorption and desorption on the resistivity.According to the effect of adsorption and free nitrogen on the resistivity of dry coal, the change mechanism of nitrogen on coal resistivity is analyzed. The adsorption of nitrogen by the coal is an exothermic process. The adsorption heat released by the coal reduces the surface energy of the pores, and the binding effect of the coal on the electrons is weakened. The electrons are easy to migrate on the surface of the coal pores, resulting in enhanced conductivity of coal and the decrease in resistivity. The nitrogen molecules penetrate into the coal pores, causing a certain expansion of the coal skeleton. The higher the nitrogen pressure in the coal is, the greater the expansion effect becomes, and the weaker the interaction between the molecules will be. Therefore, the conductive energy barrier and the resistivity of the coal are all lowered.Nitrogen enters the pores and fissures of the coal and forms a thin adsorption layer on the surface. The sorbed nitrogen reduces the surface free energy of pores and fissures in the coal, and its binding effect on electrons is weakened, making their transition easier. And the resistivity decreases.

In the process of nitrogen seepage in the coal, the changes of coal cracks all have an impact on the resistivity. The research shows that the coal crack evolution plays a major role in the conduction channel, when the conduction channel is damaged, the resistivity increases;the coal ruptures to form a macro fracture surface , which greatly cuts off the conductive channel of the coal, and the coal resistivity continues to show an upward trend.

The resistivity response characteristics of coal samples with continuous nitrogen injection are analyzed as follows: in the initial stage of nitrogen action (0~60s), it is the process of initial operation and pressure accumulation of the gas injection equipment, the pressure in the borehole is maintained at 0.1MPa, and the influence of adsorption effect on coal resistivity is not obvious. With the end of the applied nitrogen pressure accumulation, the pressure rises and fluctuates, which reflects the small expansion of the coal fractures; at this time, the increase of the resistivity due to the expansion of the cracks is greater than the decrease of the resistivity caused by the adsorption of nitrogen in the coal, and the resistivity rises slowly. When the applied nitrogen pressure reaches the crack initiation pressure of the coal, the coal breaks, the nitrogen gas is released and desorbed, the conductive channel is destroyed, and the resistivity jumps upward.

The Enlightenment of the Test Results on the Coal Cracking Behavior

The resistivity indicates the formation of coal fracture space, reflects the development of fractures in the process of nitrogen-induced coal fracture, and is a manifestation of the degree of coal fracture damage. The resistivity can quantitatively evaluate the degree of coal fracture failure. When the nitrogen pressure reaches the maximum value, the resistivity curve has not yet jumped, which means that after reaching the crack initiation pressure, the coal fractures continue to develop and the coal resistivity increases slowly. These micro-cracks may be the initial form of the later large cracks. Under the action of nitrogen pressure, some micro-cracks will develop into large cracks until destroyed, and the resistivity will suddenly increase. The injection of nitrogen into the coal leads to an increase of the crack space, but the nitrogen cannot be fully coupled with the space, resulting in an increase in coal resistivity. When the nitrogen pressure starts to rise, the pore wall begins to inoculate or activate micro-cracks, and the crack space increases. Fracture growth requires nitrogen to continuously fill the fracture space.Nitrogen is stored in the crack space and acts on the crack surface, causing it to suffer tensile failure continuously.

Conclusion

A resistivity test system of uniaxial nitrogen-fractured coal was established, and the influence of resistivity in the process of nitrogen-fractured coal under different axial pressures was studied. In the process of nitrogen injection into the coal, the greater the axial pressure is, the greater the crack initiation pressure of the coal is, and the shorter the crack initiation time is. The coal resistance remains basically stable at first, then rises in shock, and finally jumps sharply.The evolution mechanism of coal resistivity during nitrogen injection was discussed. Nitrogen adsorption of coal can reduce its resistivity, and crack expansion can effectively cut off coal’s conductive channel and improve coal's resistivity.

Acknowledgments

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Nomenclature

ρ - resistivity of coal, [Ω·m]

S - cross-sectional area of the coal sample, [m^2]

L_1 - length between the two measuring points, [m]

R_m - resistance of coal, [Ω]

R_0 - initial resistance of the coal, [Ω]

ρ_0 - initial resistivity of the coal, [Ω·m]

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