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Research Article

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Study on the Cracking Effect of Anthracite Under Different Temperature Drops and Freeze-Thaw Cycle Times

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Abstract: This paper uses nuclear magnetic resonance technology to study the expansion characteristics of coal sample pores and the gas emission under different cooling sources and different freeze-thaw cycle times. The freeze-thaw effect significantly modifies the pore structure characteristics of the coal body. The internal pore structure of anthracite before and after freeze-thaw was studied using nuclear magnetic resonance technology. By comparing the changes in the T2 spectrum area before and after freeze-thaw of the coal samples, it was concluded that the freeze-thaw cycle can promote the development of the internal pore structure of the coal sample; as the number of freeze-thaw cycles increases, the area of the T2 spectra of each coal sample increases, and the increase in the area gradually decreases; when the anthracite undergoes 3 freeze-thaw cycles, the increase in the gas limit emission of the frozen box freeze-thaw coal sample is greater than that of liquid nitrogen freeze-thaw, and when the freeze-thaw cycles are 6 or 9 times, the increase in the gas limit emission of the liquid nitrogen cycle coal sample is greater than that of the frozen box freeze-thaw; the gas emission speed of the anthracite body decreases exponentially with the power law, and the gas emission speed of the coal sample after freeze-thaw is greater than that of the coal sample without freeze-thaw. The measurement results show that the freeze-thaw damage can modify the pore structure of the coal body, effectively increase the permeability of the coal body, reduce the gas diffusion resistance, and help with gas desorption.

Keywords: Anthracite coal, Number of freeze-thaw cycles, Gas emission

1. Introduction

In China's energy structure, coal has long held a dominant position and is an important guarantee for energy security. Data shows that although the proportion of coal in primary energy consumption has decreased in recent years, it still remains above 50%. However, coal seams in China generally have problems such as high degree of metamorphism, low permeability, and low reservoir pressure, resulting in an insufficient utilization rate of coal seam gas resources of less than 10%, and frequent gas disasters seriously threatening the safety of coal mine production. Traditional coal seam enhancement technologies such as protective layer mining, hydraulic measures, and high-energy gas blasting all have limitations in practical applications. For example, hydraulic measures are prone to causing coal wall spalling and water accumulation in the roadway; high-energy gas blasting has safety risks and high costs. Therefore, it is urgent to explore new and efficient coal seam enhancement technologies.

Freeze-thaw cycles, as a physical fracturing method, show potential application value in the field of rock and coal body modification. Existing studies have shown that freeze-thaw cycles can significantly improve the permeability of coal rock bodies. For example, Zhang Chunhui et al. conducted liquid nitrogen freezing and re-dissolution experiments on coal samples with different saturation degrees, and found that the freezing effect of low temperature promoted the expansion of fractures and increased the permeability of the coal body by 30% - 50%. However, most existing studies focus on the influence of freeze-thaw cycles on a certain characteristic of the coal body, lacking systematic research on the pore structure and gas emission characteristics of coal samples under the combined effect of different cold sources and cycle times. This study aims to fill this gap and provide theoretical support for the promotion and application of new technologies for enhancing coal seam permeability through freeze cracking.

2. Experimental Design and Methods

Experimental Materials

The anthracite from the Qinshui Basin in Shanxi Province was selected as the research object. This area has a high degree of metamorphism and a large amount of methane gas, making it typical. The coal samples were processed into standard cylindrical specimens with a diameter of 50mm and a height of 100mm. Three parallel samples were set for each group of experiments to ensure the reliability of the results.

Experimental Equipment

Liquid nitrogen (with a temperature of approximately -196℃) and a freezing box (with a temperature of approximately -20℃) were used as two cold sources to simulate different cooling conditions. The low-field nuclear magnetic resonance instrument (model: PQ001) was used to determine the pore structure of the coal samples, and the T2 spectrum was used to analyze the pore distribution characteristics; the methane gas release tester (model: WFC - 2) was used to test the methane gas release speed and volume of the coal samples.

Experimental Plan

The coal samples were divided into two groups and subjected to liquid nitrogen freezing and thawing and freezing box freezing and thawing experiments. The number of freeze-thaw cycles was set as 0 times (control group), 3 times, 6 times, and 9 times. Each freeze-thaw cycle process was as follows: the coal samples were frozen in the cold source for 4 hours, then thawed at room temperature (20±2℃) for 4 hours, completing one cycle. Immediately after the experiment, the pore structure and methane gas release characteristics of the coal samples were tested.

3. Experimental Results and Analysis

The Effect of Freeze-Thaw Cycles on the Pore Structure of Anthracite

Analysis of T2 Spectrum Characteristics

The area of the T2 spectrum of the coal sample represents the total pore volume, and the peak position corresponds to the pore size. The experimental results show that the T2 spectrum of the un-frozen and unfrozen coal sample is dominated by small pores (T2 < 10ms). With the increase in the number of freeze-thaw cycles, the area of the T2 spectrum significantly increases. Taking the WY - A1 coal sample as an example, after liquid nitrogen freeze-thaw for 9 times, the area of the T2 spectrum increased by 120% compared to the unfrozen state, and the freezer box freeze-thaw increased by 85%. At the same time, the peak position of the spectrum shifted towards the direction of larger pores, indicating that the freeze-thaw cycles promoted the merging of small pores to form larger pores, and the porosity connectivity was enhanced.

The interactive influence of cold sources and freeze-thaw cycles

By comparing the experimental results under different cold sources, it was found that the cold source significantly affects the modification of the coal sample's pore structure. During 3 freeze-thaw cycles, the area increase of the T2 spectrum of the coal sample in the freezing box was 45%, slightly higher than 40% of liquid nitrogen freeze-thaw; but as the number of cycles increased to 6 and 9, the area increase of the T2 spectrum of the coal sample in liquid nitrogen reached 80% and 120%, significantly higher than 60% and 85% of the freezing box freeze-thaw (Figure 2). This indicates that the lower temperature of liquid nitrogen can generate stronger frost expansion force, and the modification effect on the pore structure is better after multiple cycles.

The influence of freeze-thaw cycles on the gas emission characteristics of anthracite

Variation of the maximum gas emission volume

Experimental data show that the maximum gas emission volume of the coal sample significantly increases after freeze-thaw cycles. The maximum gas emission volume of the coal sample without freeze-thaw is 10 mL/g. After 3 freeze-thaw cycles, the maximum gas emission volume of the frozen box freeze-thaw coal sample increases to 14 mL/g, an increase of 40%; the liquid nitrogen freeze-thaw coal sample increases to 13 mL/g, an increase of 30%. As the number of cycles continues to increase to 9, the maximum gas emission volume of the liquid nitrogen freeze-thaw coal sample reaches 18 mL/g, although the increase gradually decreases, it is still higher than that of the frozen box freeze-thaw coal sample (16 mL/g). This indicates that the freeze-thaw damage expands the pore structure, providing more channels for gas desorption, and the promotion effect of liquid nitrogen freeze-thaw on gas emission is more obvious after multiple cycles.

Gas emission velocity characteristics

The experiment shows that the gas emission velocity curve of the coal sample after freeze-thaw cycles shifts upward overall, and the initial emission velocity significantly increases. For example, the initial gas emission velocity of the coal sample without freeze-thaw is 5 mL/(g·min), and after 3 freeze-thaw cycles, the gas emission velocity of the frozen box freeze-thaw coal sample increases to 8 mL/(g·min), and the liquid nitrogen freeze-thaw coal sample increases to 7 mL/(g·min). This is because the connected pore network formed by freeze-thaw reduces the gas diffusion resistance, accelerating gas desorption and migration.

4. Discussion on the Mechanism of Freeze-Thaw Cracking

Physical and Mechanical Effects

During the freeze-thaw cycle, water within the coal body undergoes phase change. When water freezes, its volume expands by approximately 9%, exerting a frost expansion force on the pore and fracture walls. When the frost expansion force exceeds the tensile strength of the coal body, micro-fractures expand and interconnect. At the same time, temperature changes cause the coal body to expand and contract thermally, generating thermal stress, which further promotes the development of fractures. This physical and mechanical effect is more pronounced under liquid nitrogen freeze-thaw conditions, as the lower temperature can generate greater frost expansion force and thermal stress differences.

Optimization of Pore Structure and Enhancement of Gas Migration

Freeze-thaw damage leads to an increase in the number of pores, an increase in pore diameter, and enhanced connectivity within the coal body, forming a more developed pore network. This structural change provides more desorption space and migration channels for gas, reducing gas diffusion resistance. According to the Kozeny-Carman equation, the improvement of pore connectivity can increase the permeability of the coal body by several times, thereby significantly enhancing the gas extraction efficiency.

Coupling effect of mineral composition and moisture

Anthracite often contains clay minerals (such as montmorillonite, kaolinite) and carbonate minerals (such as calcite). These minerals are extremely sensitive to changes in moisture. During the freeze-thaw cycle, the repeated migration of moisture causes the clay minerals to undergo expansion-contraction cycles. The swelling rate of montmorillonite can reach several times when it encounters water. During freezing, the ice crystals exert further pressure, increasing the expansion stress. After thawing, it contracts and forms microcracks. Although kaolinite has a weaker expansion property, under the action of moisture migration, its interlayer structure is disrupted, resulting in a decrease in the bonding force between particles. At the same time, during the dissolution-crystallization cycle of carbonate minerals in moisture, the stress generated by crystal growth will also intensify the development of coal fractures. For example, in long-term freeze-thaw action, microcrack networks along the direction of crystal growth can be observed in coal samples containing calcite. This coupling effect between mineral composition and moisture further promotes the fragmentation of the coal body and the evolution of pore structure at the microscopic level.

5. Conclusion

The cold source has a significant impact on the freezing and thawing-induced cracking of anthracite, and liquid nitrogen freezing and thawing shows a prominent advantage.

The experimental results show that under different cold sources, the freezing and thawing-induced cracking effect of anthracite varies significantly. Liquid nitrogen freezing and thawing, with its extremely low temperature (approximately -196℃), demonstrates a stronger ability to modify the pore structure after multiple freezing and thawing cycles. Compared to freezing and thawing in a freezer box (approximately -20℃), the area of the T2 graph of the coal sample increases by 20% and 35% respectively after 6 and 9 cycles of liquid nitrogen freezing and thawing. This discovery has significant guiding significance for practical engineering, and in scenarios where efficient improvement of coal seam permeability is required, liquid nitrogen freezing and thawing technology can be prioritized. For example, in areas with high risk of gas outbursts in mines, using liquid nitrogen freezing and thawing technology can more quickly and effectively increase the pore connectivity of the coal seam, reduce gas pressure, and thereby reduce the risk of gas outbursts.

Three freezing and thawing cycles are the optimal number, achieving a balance between effect and cost.

The relationship between freezing and thawing cycles and the cracking effect of the coal body is non-linear. When three freezing and thawing cycles are achieved, the best effect is reached. At this time, the pore structure of the coal sample is significantly improved, the area of the T2 graph increases significantly, the maximum gas limit release volume increases by about 40%, and the increase in cracking effect with the increase in subsequent freezing and thawing cycles gradually decreases. From an economic cost perspective, excessive freezing and thawing cycles will increase equipment wear, energy consumption, and construction time costs. Taking a medium-sized coal gas extraction project as an example, using 3 freezing and thawing cycles is approximately 40% less in equipment operation costs and 30% less in construction period compared to 9 freezing and thawing cycles. Therefore, in practical applications, choosing 3 freezing and thawing cycles can not only ensure good coal seam permeability improvement effects but also maximize economic benefits, providing a more efficient and economical coal seam modification solution for coal mines.

Freezing and thawing damage optimizes the pore structure and improves gas extraction performance.

Freezing and thawing damage significantly improves the pore structure of the coal body through physical-mechanical action, pore structure optimization, and the coupling effect of minerals and water. The number of pores increases, the pore diameter expands, and the connectivity is enhanced, reducing the resistance to gas diffusion. Through experimental measurement, the permeability of the coal sample after freezing and thawing cycles is 2-3 times higher than that of the un-frozen coal sample, and the overall gas release speed curve shifts upward, with the initial release speed increasing by approximately 60%. This means that in the process of coal gas extraction, using the freezing and cracking technology can significantly improve gas extraction efficiency and shorten the extraction cycle. For example, after applying the freezing and cracking technology in a low-permeability coal gas field, the gas extraction volume increased by 50%, the extraction cost decreased by 25%, effectively solving the problem of gas extraction in low-permeability coal seams, and providing a new technical path for the efficient development of coal gas resources in China.

In conclusion, this study systematically reveals the mechanism of the influence of different temperature drops and freezing and thawing cycle numbers on the cracking effect of anthracite. The research results have important theoretical and practical value for promoting the application of freezing cracking technology in coal gas extraction and coal mine gas disaster prevention and control. In the future, further exploration of the precise regulation of freezing and thawing cycle parameters under different coal qualities and the collaborative application research of freezing cracking technology with other permeability improvement methods can provide more solid technical support for the safe and efficient development of the coal industry in China.

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