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# Research on Acidizing Fracturing Based on Matrix - Fracture Interaction Permeability Model of Coal Seam

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**Abstract:**
With the normalization of deep mining, scientific challenges are increasingly complex, particularly in managing and mining deep high-gas mines. For safe and efficient operations, gas treatment is essential before coal extraction to reduce gas content and pressure to safety standards. By quantifying coal's structural characteristics and understanding gas migration behavior, the mechanisms behind increased permeability is explored. To quantify the impact of gas adsorption on crack deformation, we define an internal expansion coefficient that represents the ratio of crack deformation due to gas adsorption relative to matrix deformation. It is analyzed that crack growth is influenced by principal stress magnitude and direction. Through quantitative characterization of coal structure, we analyze gas migration characteristics within it and investigate how strong oxidizing agents enhance oxidation yield. Based on the ternary coal industry's engineering context, we conduct a technology process analysis and verify application effects for acidizing combined with fracturing stimulation techniques.

**Keywords:** permeability; matrix - fracture; acidizing fracturing; increasing permeability technology; gas transport.

## INTRODUCTION

Under mining stress, fractures inevitably develop in the coal seam behind the working face [1]. Zhang states that the expansion of pore structures not only deteriorates coal's mechanical properties but also alters gas migration pathways, impacting gas extraction [2]. This indicates a close relationship between gas extraction and the degree of fissure development in coal [3]. Yuan points out that primary fractures form during complex geological movements, leading to new fracture networks under mining activities [4]. Wang et al. and Zhao et al. note that continuous deformation of coal bodies in different environments results in varying degrees of fracturing [5,6]. Numerous studies show that coal mass failure occurs gradually as it breaks from weak deformation under various stress conditions [7,8].

It can be seen from Figure 1 that the spatial distribution of three-dimensional cracks in coal body is very complex. When the three-dimensional cracks are observed from different angles, it can be clearly seen that a large number of microscopic cracks surround the main cracks, and the two are basically in a state of both merging and separating.

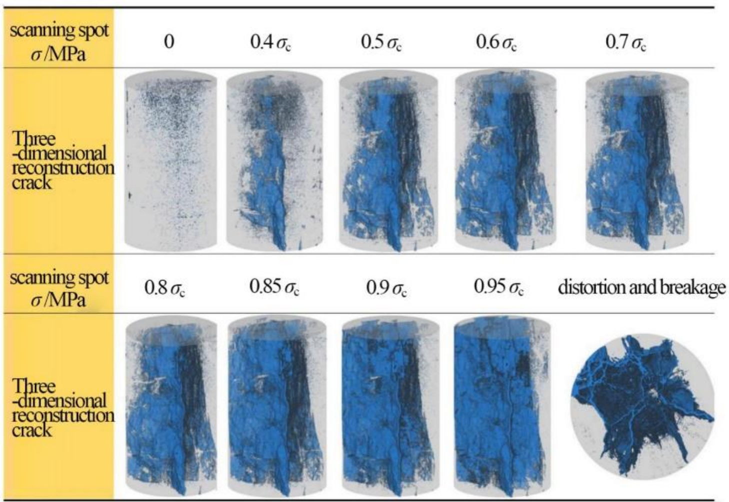



Figure 1. Crack propagation morphology and spatial distribution in the process of sandstone

### Mechanism of Increasing Yield and Increasing Permeability by Strong Oxidant

According to Zhang, the mechanism of increasing production and reflection by strong oxidizing agents involves reforming coal seam structures through the injection of fracturing slurry with strong oxidizing properties [9]. Li notes that strong oxidizing fracturing slurries primarily consist of acids, persulfates, potassium permanganate, peroxides, and chlorine dioxide [10]. This technology achieves dual effects—corrosion and yield increase—by injecting strong oxidation liquids into coal seams for oxidation. Pan et al. and Yuan et al. explain that acid injection enhances coal reservoir permeability by dissolving minerals and blockages within the coal body, thereby improving connectivity between pore cracks [11,12].

Inorganic acids are chemically active and react quickly with minerals, while organic acids are weaker and react more slowly but penetrate better during acidizing fracturing [13]. The Dissolution behavior of coal by acid is influenced by the principles, modes, and processes of the acidification reaction, focusing on changes in surface morphology of coal and rock during this process [14,15].

### Engineering Background

No. 3 coal seam is mined on the 4302 fully mechanized caving face in Sanyuan Coal Mine. The north is the boundary of the mine field, the average thickness of the coal seam is 7.25m, and the inclination of the coal seam is 1~11°. The design length of 4302 fully mechanized caving face is 220 m, and the length of inlet and return air lanes is 1197 m and 1348 m, respectively. Face shearer mining 3 m high coal seam, the rest of the coal thickness is mined through coal drainage, the goaf gradually caved with the advance of the working face. According to the design requirements, the mining length of the working face is 991 m, the recoverable coal reserves are 2.36 million tons, and the mining cycle is 0.9 a.

## METHOD

### The Permeability Model of Coal

#### *Matrix - fracture interaction model of coal seam*

In the mining process of deep coal resources, it is very important to consider the influence of gas adsorption and desorption and creep deformation to evolve the seepage characteristics of the coal body in front of the work, as shown in Figure 2a, 2b and 2c [16]. Assuming the presence of contact points and mineral fillers inside the fracture, the influence of matrix deformation caused by gas adsorption on fracture deformation and coal deformation is studied. As shown in Figure 4g, the matrix adsorption expansion deformation  includes two parts: fracture deformation and coal deformation. In order to quantify and characterize the effect of gas adsorption on fracture deformation, an internal expansion coefficient f representing the ratio of fracture deformation caused by gas adsorption to matrix deformation is defined as follows:

$$\Delta V_m^s = \Delta V_b^s + \Delta V_f^s \tag{1}$$

$$\Delta V_f^s = f\Delta V_m^s, \Delta V_b^s = (1-f)\Delta V_m^s \tag{2}$$

#### *Gas transport characteristics*

Wu states that the main purpose of gas extraction is to remove gas from coal seams, thereby reducing gas disaster occurrences [17]. Thus, understanding the mechanism of gas transport is essential. Fan and Li et al. describe coal seam gas extraction as a process involving gas desorption, diffusion, and seepage. In a ‘three highs and one disturbance’ engineering geological environment, deep coal seam gas extraction presents a multi-field coupling challenge [18,19]. Weinotes that coal creep deformation, thermal expansion of the coal matrix, and gas adsorption expansion significantly affect the permeability characteristics of the coal medium [20]. Wang et al. emphasize that interactions between matrix-fractures due to thermal expansion and gas adsorption also contribute to these challenges [21]. Consequently, the difficulty in extracting gas is closely linked to the storage conditions within the coal seam [22]. By examining both the intrinsic properties of coal seams and their engineering geological environments, we can identify mechanisms for gas transport and influencing factors to provide theoretical guidance for key technologies in coal mine gas extraction [23,24].

### Key Technology of Acidification-Fracturing Composite Permeation

The combination of acidizing and fracturing for increasing permeability of coal seam is not a simple addition of the increasing permeability technology of hydraulic fracturing and acidizing fracturing, which interact and influence each other in the increasing permeability process. Some scientific problems, such as how acid can promote the further extension of fractures, the effect of fracturing technology on acidification reaction, and the permeability change law of coal seam under multi-field coupling, are worthy of further study. Research ideas on key technologies of acidizing and fracturing gas extraction are shown in Figure 3.

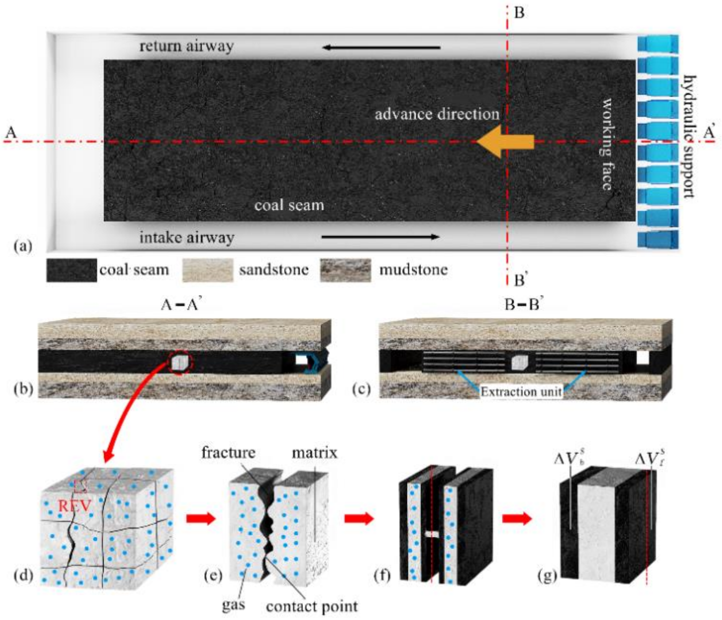



Figure 2. Schematic diagram of actual problems. (a) Schematic diagram of working face; (b) A-A’ cross section of coal seam; (b) B-B’ cross section of coal seam; (d) Coal structure model; (e) Fracture REV model; (f) Matrix-fracture interaction model; (g) Conceptual map for matrix swelling deformation

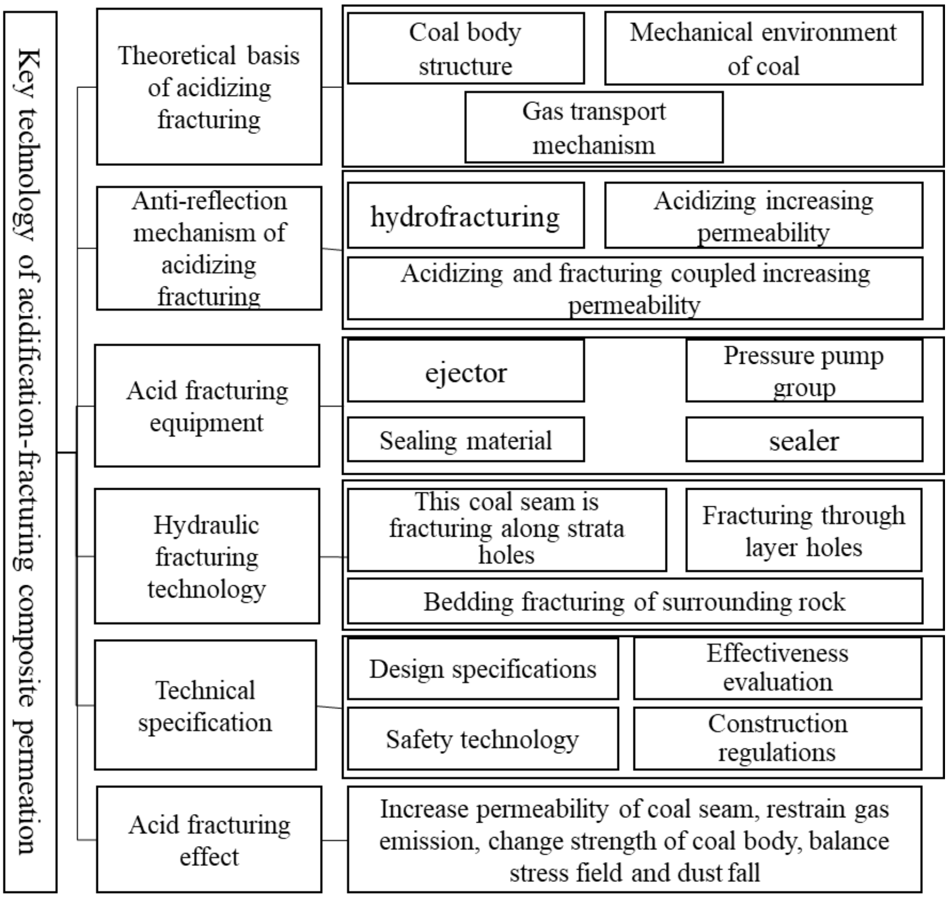



Figure 3. Research idea of key technology of acidizing fracturing gas extraction

***Acidification and fracturing composite increasing permeability technology***

The acidizing and fracturing technology for underground coal mines can be optimized based on the fracturing object, drilling type, and acidizing method to enhance gas extraction efficiency across various geological conditions. In this test, a bedding drilling and fracturing approach was used. The test area was located 1000m from the opening of the 4302 transport groove, with four groups of test holes designed—each containing five holes spaced 10m apart.

In this experiment, segmented point fracturing was utilized with each group of drilling holes undergoing three stages of fracturing. The first, second, and third groups consist of pressure intermediate holes, spaced 2, 3, 4 and 5m from the other holes. Each hole is designed to be 80m deep with a diameter of 94mm and an opening height of 2.2m; the angle varies according to the coal seam and has a sealing depth of 15m.The fourth group also contains pressure intermediate holes with spacing between them and other holes set at 2, 3, 5 and 10m. These holes share the same design specifications: an overall depth of 80m, aperture size of 94mm, opening height of 2.2m, sealing depth of 15m, while their inclination varies with the coal seam as illustrated in Figure 4.

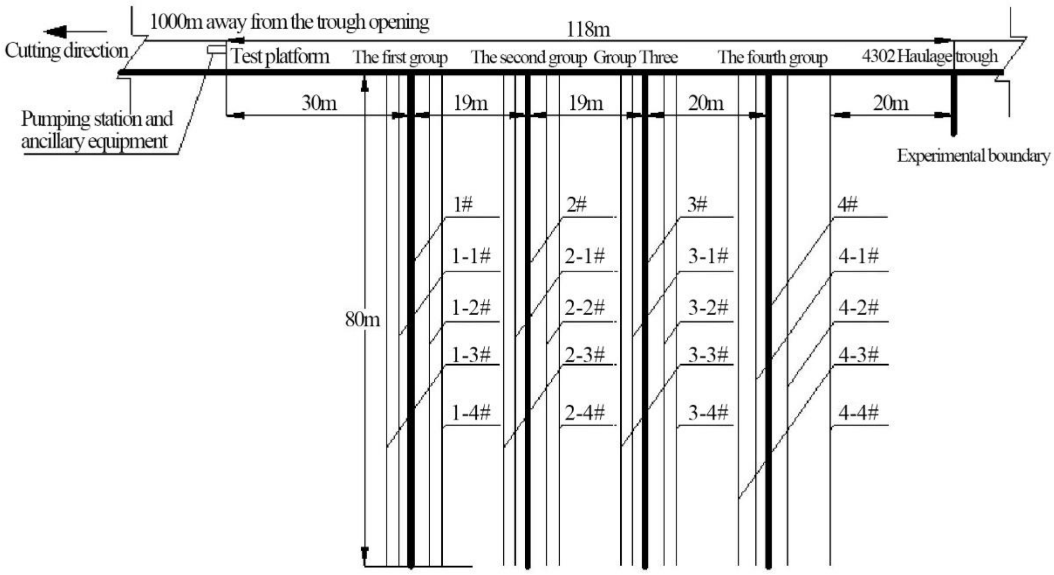



Figure 4. Acid fracturing borehole layout

The second group and the third group had better drilling effect, and transverse pilot cracks were formed between the pressure hole and the observation hole, and high-pressure acid was derived from the observation hole. The whole fracturing process lasted about 30 minutes, and the liquid injection volume of each stage was about 2m$^3$. The fracturing process of acidizing fracturing is shown in Figure 5.

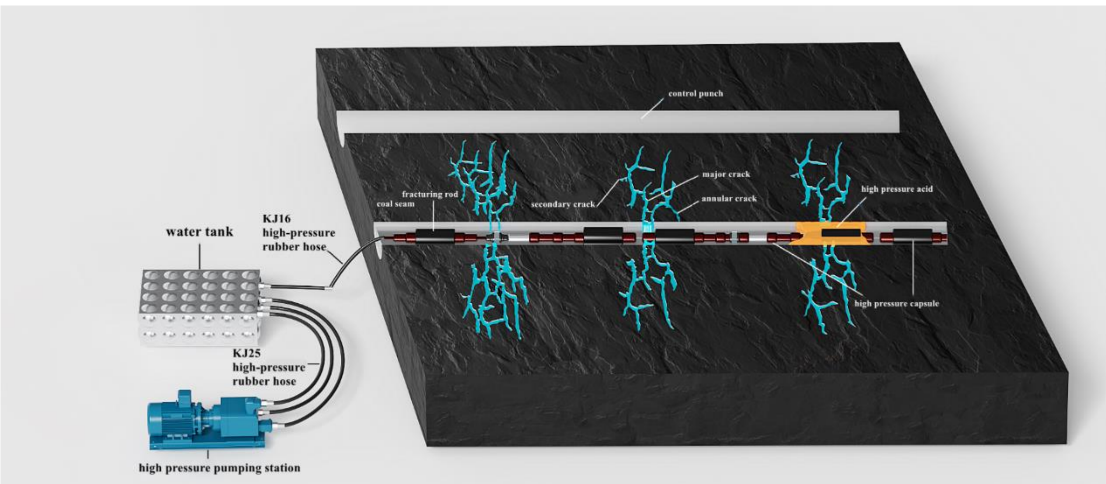
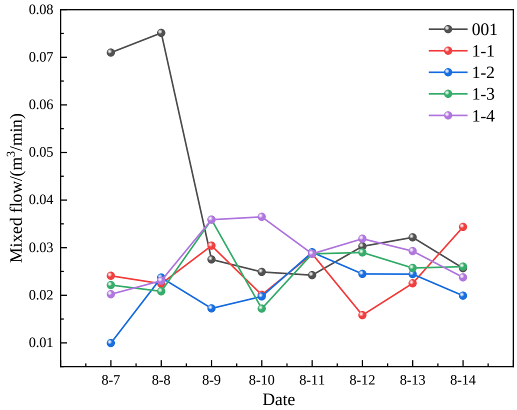



Figure 5. Diagram of acid fracturing process

## RESULTS ANALYSIS

### Application Effect of Acidification and Fracturing Combined Increasing Permeability Technology

After the fracturing experiment, additional observation holes were created and connected to the pumping system. The gas concentration, flow rate, and negative pressure from both acidizing fracturing test holes and normal drilling holes were continuously monitored using the CJZ70 parameter tester. The variations in gas mixed flow rate and concentration across four groups of drilling holes are illustrated in Figures 6 to 11.

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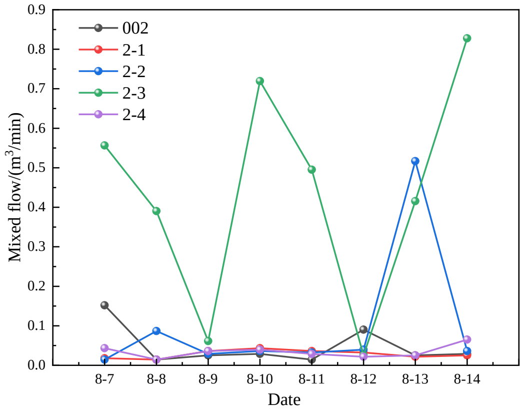


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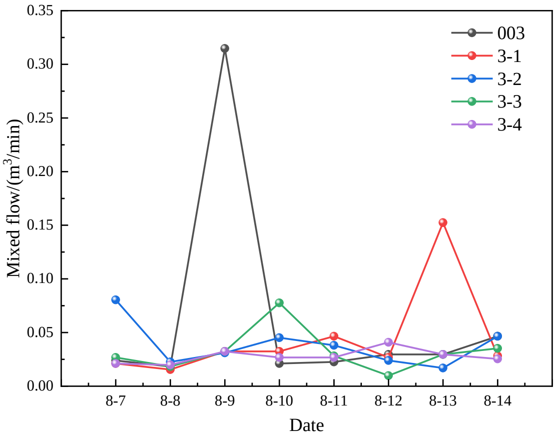


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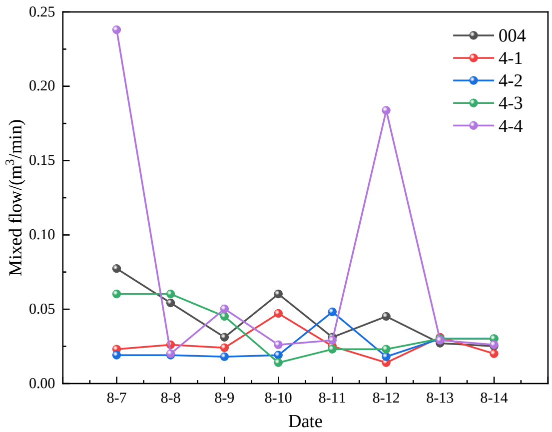
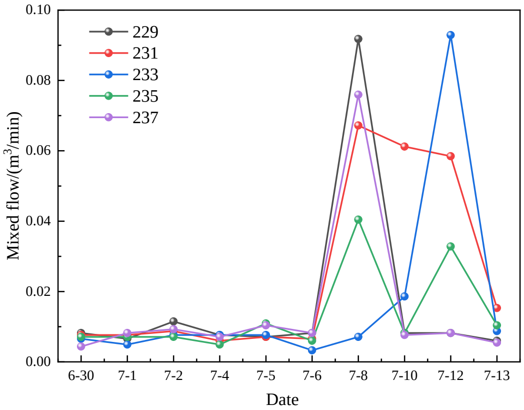



Forth group

Figure 6. Variation diagram of mixed flow rate of borehole gas extraction after acidizing and fracturing of coal seam

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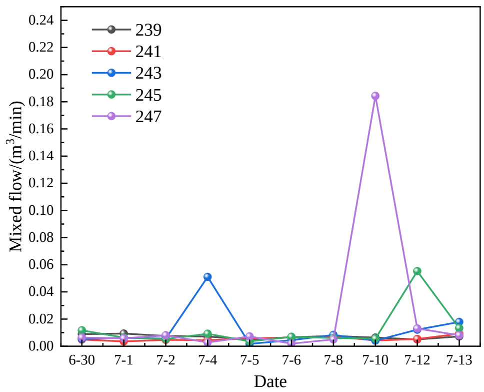
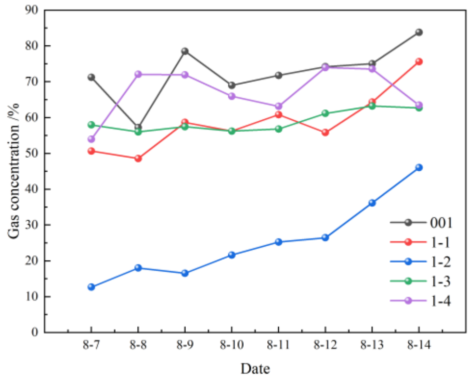



Second group

Figure 7. Variation diagram of mixed flow of gas extraction in common borehole of coal seam

As shown in Figure 6 and 7, through continuous observation of acidizing and fracturing test holes and analysis of test data compared with ordinary extraction drilling holes, it is concluded that: After acidizing and fracturing test, the mixed flow rates of gas extraction in single hole of the four drilling groups are 0.01~0.075m$^3$/min, 0.011~0.83m$^3$/min, 0.01~0.314m$^3$/min and 0.012~0.237m$^3$/min, respectively. The average mixed flow rates of each group were 0.027m$^3$/min, 0.136m$^3$/min, 0.041m$^3$/min and 0.041m$^3$/min, respectively. The mixed flow rate of gas extraction from single hole of common borehole in this coal seam is 0.003~0.182m$^3$/min, and the average mixed flow rate is 0.015m$^3$/min. After acidizing fracturing, the average mixed flow rate of acidizing drilling group was nearly 3 times higher than that of ordinary drilling group. It shows that acidizing and fracturing can effectively improve the fracture development of coal seam, increase the connectivity between the fracture and the extraction borehole, and then increase the effective extraction flow of the borehole.

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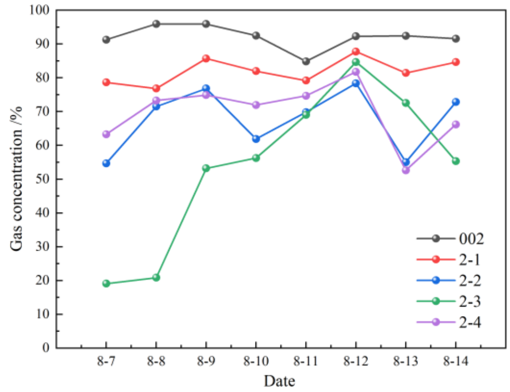


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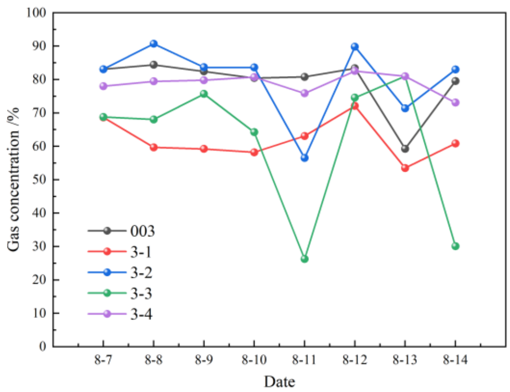


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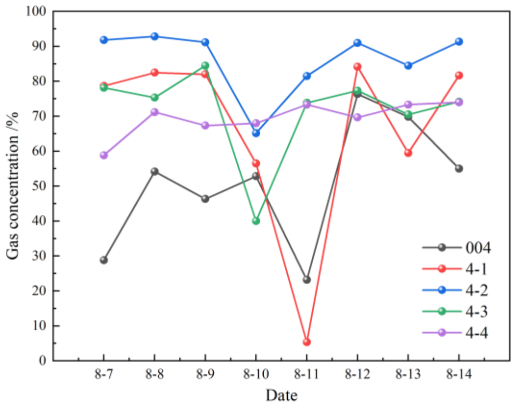


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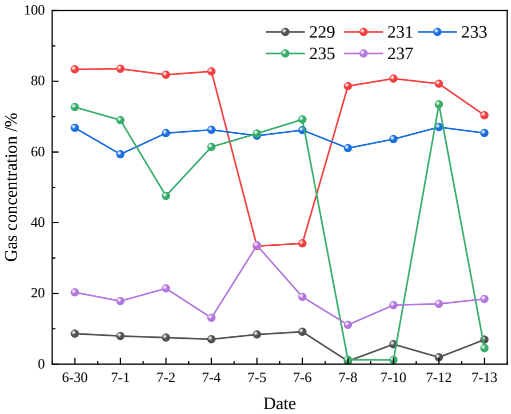
Figure 8. Variation diagram of gas extraction concentration in borehole after acidizing and fracturing of coal seam

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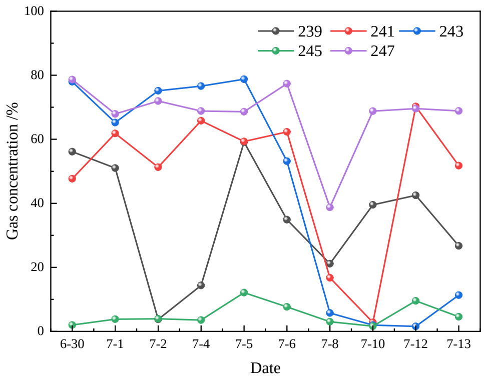
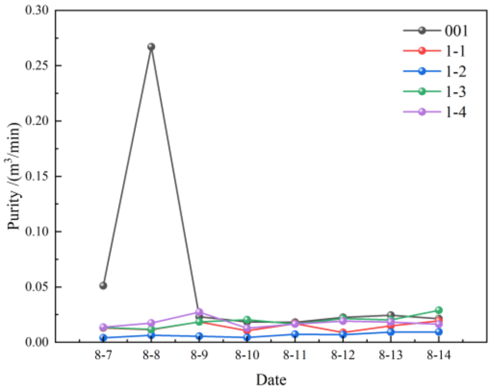



Second group

Figure 9. Variation diagram of gas concentration in common borehole of coal seam

As shown in Figure 8 and 9, it can be seen from the above Figure that after acidification, the concentration of gas extraction from a single hole of the four groups of boreholes is 12.8~83.2%, 18.4~95.2%, 63.1~95.1%, and 52.4~96.1%, respectively. The average gas extraction concentration in each group is 56.1%, 72.6%, 85.9% and 84.2%, respectively. The single-hole gas concentration of common borehole in this coal seam is 0.8%~84.1%, and the average single-hole concentration is 40.63%. After acidizing fracturing, the average single-hole concentration of acidizing drilling group is increased by nearly 50% compared with that of ordinary drilling group. Compared with the gas concentration data, the effect of acidizing and fracturing effectively increases the gas permeability of the coal body, the permeability enhancement effect is better, the gas desorption amount of the borehole is increased, and the gas extraction concentration of the borehole is increased.

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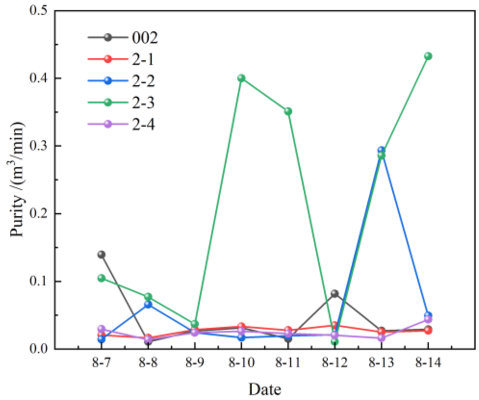


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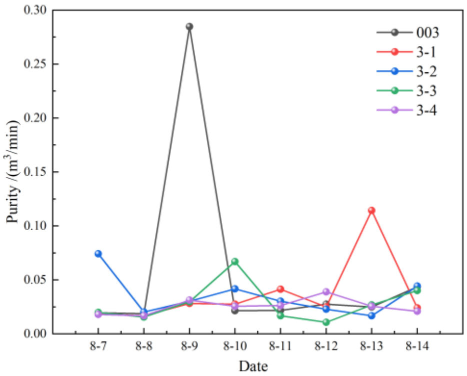


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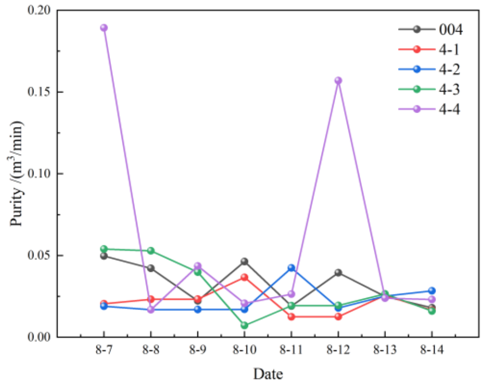
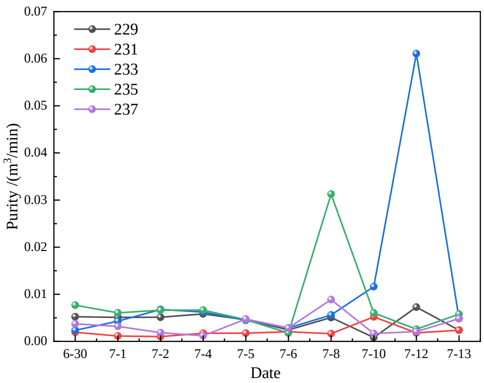



Forth group

Figure 10. Variation diagram of gas extraction net amount in borehole after acidizing and fracturing of coal seam

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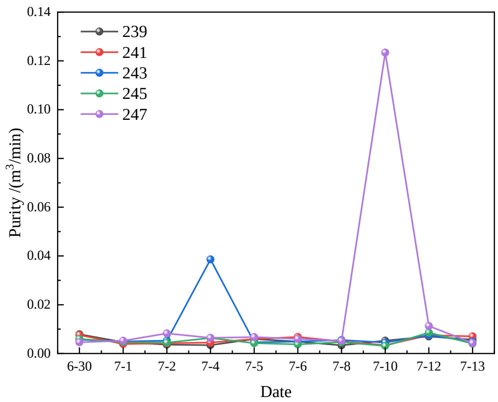


Second group

Figure 11. Variation diagram of pure gas extraction from common borehole in this coal seam

It can be seen from Figure 10 and Figure 11 that after acidification, the pure gas extraction from single hole of the four groups of drilling holes is 0.001~0.266m$^3$/min, 0.010~0.434m$^3$/min, 0.009~0.285m$^3$/min, and 0.013~0.188m$^3$/min, respectively. The average pure flow rate of a single hole is 0.041 m$^3$/min, and the pure gas extraction in a single hole of a common borehole in this coal seam is 0.00006~0.125m$^3$/min, and the average pure gas extraction in a single hole is 0.006 m$^3$/min. After acidizing, the average gas extraction purity of single hole is increased by 6.8 times, and the gas extraction effect of acidizing and fracturing borehole is obviously better than that of ordinary borehole.

It can be seen from Figure 10 to Figure 11 that in the four groups of acidizing and fracturing boreholes, the average single-hole mixed flow rate of pressure fracture holes was 0.039m$^3$/min, 0.047m$^3$/min, 0.064m$^3$/min, and 0.043m$^3$/min respectively. The average single-hole gas extraction concentration was 72.1%, 91.5%, 89.3% and 74.4%, respectively. The average single-hole net flow is 0.055m$^3$/min, 0.043m$^3$/min, 0.057m$^3$/min and 0.032m$^3$/min, respectively. In general, the gas extraction concentration, extraction mixed flow and extraction net flow in the pressure fracture hole are higher than those in other observation holes.

As can be seen from the comparison between the second group of Figure 6 and the second group of Figure 11, the average gas extraction mixed flow rate in observation hole No. 2-3 is 0.427m$^3$/min, which is much higher than the overall average gas extraction mixed flow rate of 0.059m$^3$/min.

As can be seen from the comparison between the third group of Figure 6 and the third group of Figure 8, the average mixed flow rate of gas extraction in pressure hole 003# is 0.064m$^3$/min. The average gas extraction mixed flow rates of observation holes 1 to 4 were 0.044m$^3$/min, 0.038m$^3$/min, 0.032m$^3$/min and 0.028m$^3$/min, respectively. In general, the closer the distance between the observation hole and the pressure hole, the better the extraction effect.

As can be seen from the fourth group of Figure 6 and the fourth group of Figure 8, the distance between the fourth group of pressure holes and the observation holes is 10m, and the excessive distance leads to the failure of the transverse cracks between the pressure holes and the observation holes, and finally some circumferential micro-cracks are formed around the high-pressure expansion capsules in the pressure holes. In the drilling group, the average mixed flow rate of gas extraction in a single hole is 0.041m$^3$/min, the average concentration of gas extraction in a single hole is 84.26%, and the average pure flow rate of gas extraction in a single hole is 0.034m$^3$/min, which is still much better than the data of ordinary drilling.

## CONCLUSIONS

Gas extraction is closely related to the development of fissure structures in coal. Mining operations create a fracture network that facilitates gas seepage. Gas extraction involves desorption, diffusion, and seepage processes. Factors such as coal creep deformation, thermal expansion of the coal matrix, and gas adsorption expansion significantly affect the permeability of coal. The challenge in enhancing flow in high-stress, low-permeability seams arises from dense pore structures and poor permeability, leading to low gas extraction efficiency. The main measures to enhance coal seam permeability include improving the structural permeability and increasing the pressure gradient. Acidizing fracturing enhances permeability through acid-driven processes. High-pressure acid supports fracture formation within the coal body, creating an interwoven fracture network that facilitates increased diffusion and migration pathways for gases. Additionally, acid injection improves connectivity between pores and fissures in the coal matrix via chemical reactions like dissolution and corrosion. This technology has been successfully applied in extracting gas from No. 3 coal seam (low-gas seam) at Sanyuan Coal Mine with positive results.

(1) To quantify the effect of temperature on coal permeability, utilizing thermodynamics and rock mechanics, a coal porosity model that considers creep, thermal effects, and seepage from the perspectives of thermal expansion deformation, creep deformation, and gas adsorption is established.

(2) The increasing permeability of acidizing fracturing is driven by acid. High-pressure acid supports and splits the coal body, forming an interwoven fracture network that enhances gas diffusion and migration channels, thus increasing coal seam permeability. Additionally, acid injection improves connectivity between pores and fissures in the coal body, enhancing conductivity and gas permeability through chemical reactions like dissolution and corrosion. This technology has been successfully applied to gas extraction from the No. 3 coal seam (low gas seam) at Sanyuan Coal Mine, yielding positive results.

## ACKNOWLEDGEMENTS

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