ANALYSIS OF GAS MIGRATION PATTERNS IN FRACTURED COAL ROCKS UNDER ACTUAL MINING CONDITIONS

by

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Fracture fields in coal rocks are the main channels for gas seepage, migration, and extraction. The development, evolution, and spatial distribution of fractures in coal rocks directly affect the permeability of the coal rock as well as gas migration and flow. In this work, the Ji-15-14120 mining face at the No. 8 Coal Mine of Pingdingshan Tian'an Coal Mining Co. Ltd., Pingdingshan, China, was selected as the test site to develop a full-parameter fracture observation instrument and a dynamic fracture observation technique. The acquired video information of fractures in the walls of the boreholes was vectorized and converted to planarly expanded images on a computer-aided design platform. Based on the relative spatial distances between the openings of the boreholes, simultaneous planar images of isolated fractures in the walls of the boreholes along the mining direction were obtained from the boreholes located at various distances from the mining face. Using this information, a 3-D fracture network under mining conditions was established. The gas migration pattern was calculated using a COMSOL computation platform. The results showed that between 10 hours and 1 day the fracture network controlled the gas-flow, rather than the coal seam itself. After one day, the migration of gas was completely controlled by the fractures. The presence of fractures in the overlying rock enables the gas in coal seam to migrate more easily to the surrounding rocks or extraction tunnels situated relatively far away from the coal rock. These conclusions provide an important theoretical basis for gas extraction.

Key words: *gas-flow, field test, fracture network, evolution characteristics*

Introduction

Fracture fields in coal seams are the main channels for gas seepage, migration, and extraction. The development, evolution, and spatial distribution of fractures directly affect the permeability and the migration/flow of gas in fractured coal rocks. People realized the existence of fractures in coal as early as the 19th century. Former Soviet researchers Elune [1] theoretically analyzed the effects of gas on the micro-structure of coal. With the increase in prospecting and development of coal seam gas, research on fracture fields in coal gained momentum in the 1960s. In addition, fractures in coal seams provide the basis for co-extraction of coal and

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gas [2]. Therefore, understanding the mechanisms for the development and evolution of mining-induced fractures in a rock layer overlying the mining face as well as developing inversion methods have become key issues requiring urgent attention. In their book Fractures in Coal, former Soviet researchers Ammosov and Eremin [3] systematically studied the distribution of fractures in coal. Smyth and Buekley [4] studied various fracture structures in coal at the microscopic scale. Tien [5], Jha *et al.* [6], and Yasitli and Karmakar [7] made comparative analyses of the deformation and displacement of stress and fracture development in thick coal seams through numerical simulation. Qian *et al.* [8-10] proposed a dominant stratum theory and revealed the "O"-shaped circular characteristics of fractures. Xu *et al.* [11] studied how the properties of the overlying rock layer affect fracture zones, revealing the mechanism by which mining induces the development of fracture zones, and discussed the morphological distribution of mining-induced fracture zones. Yang *et al.* [12] developed a coupled flow-stress-damage model and showed how the development of mining-induced fractures causes aquifer outbursts.

Mining-induced fractures are complex and spatially distributed in a disorderly pattern. The introduction of fractals provides another approach to study mining-induced fractures. Through physical simulations, Xie *et al.* [13] and Yu *et al.* [14] revealed the fractal characteristics of mining-induced fractures in a rock layer overlying a mining face and obtained a statistical relationship between the fractal dimension of the distribution of fractures and the mining space. Zhang *et al.* [15] verified the fractal distribution characteristics of mining-induced fractures through experimentation. Using results from field investigations, Wang *et al.* [16] studied the growth of fractures in the rock layer overlying a deep working face, revealing the fractal characteristics of the evolution of the fracture network. Gui *et al.* [17] developed a simulation method for generating fracture networks based on scaling laws.

Gas-flow patterns in coal seams are an important topic for theoretical research on gas extraction from coal mines. For this reason, numerous researchers have conducted in-depth studies on the development characteristics of fractures and gas-flow patterns in coal rocks. McKee *et al.* [18] studied the relationship between stress and the porosity and permeability of coal. Enever and Henning [19] confirmed the mutual influence between the effective stress in the coal seam and the permeability. Chen *et al.* [20] introduced an equivalent elastic modulus and effective stress coefficient to describe the effects of damage and pore pressure on the permeability of top coal behavior and established a permeability model for top coal under fully mechanized mining conditions.

Although there has been a fair amount of research into the mechanical characteristics of coal rocks and the distribution/structure of mining-induced fracture fields, the research was based on laboratory experimentation and numerical simulations. Such research can not completely reproduce field boundary conditions and reveal the physical/mechanical characteristics of coal rocks in situ. Any results obtained using these methods are inevitably different from the in-situ evolution of the fracture networks in coal seams and overlying rocks. In this research, a field test was conducted for three months at the Ji-15-14120 mining face of the No. 8 Coal Mine of Pingdingshan Tian'an Coal Mining Co. Ltd. (hereinafter referred to No. 8 Pingdingshan Coal Mine), to obtain mining-induced fracture network information. In addition, the evolution of the fracture network under working conditions was analyzed. Based on the actual mining-induced fractures, the basic gas migration pattern was calculated, providing a theoretical basis for gas extraction and guidance to regulate gas-flow.

Acquisition of field mining-induced fracture information

General information of the mining face at the test site

The No. 8 Pingdingshan Coal Mine is owned by the Zhongping Energy & Chemical Group and is known to have a relatively serious outburst problem. Situated to the east of

Pingdingshan city, China. The Ji-15-14120 mining face, selected as the test site, is located at the western end of the Ji-4 downward extended mining area and has an elevation ranging from –455 to –580 m and a buried depth ranging from 580 to 705 m. The mineable section of the face is 864 m-long in the east-west direction and is tilted in the south-north direction with a width of 190 m. The thickness of the coal seam is basically stable, ranging from 3.2 to 3.9 m with an average of 3.6 m. The dip angle of the coal seam generally ranges from 17° to 25° with an average of 22°. The coal seam has a gentle slope in the west section and a steep slope in the east section. The rock layer immediately overlying the mining face is composed of sandy mudstone with a thickness of approximately 3.0 m. The selected working face has a gas pressure of 1.6 MPa and a gas-bearing capacity of 18 m^3 per tone. This working face is classified as having an outburst risk, therefore, it is particularly important to study the generation, development and permeability of the fracture fields and its gas migration channels.

Mining-induced fracture observation

A borehole imaging instrument capable of detecting the spatial occurrence of fractures within a borehole was developed in another research project. This instrument, fig. 1, can furnish continuous, complete 2-D planar and 3-D cylindrical images of the wall of a borehole based on the acquired information (*i. e.*, borehole depth, azimuth, dip angle, and borehole wall image) using special data post-processing software. The spatial occurrence of fractures within a borehole can also be calculated.

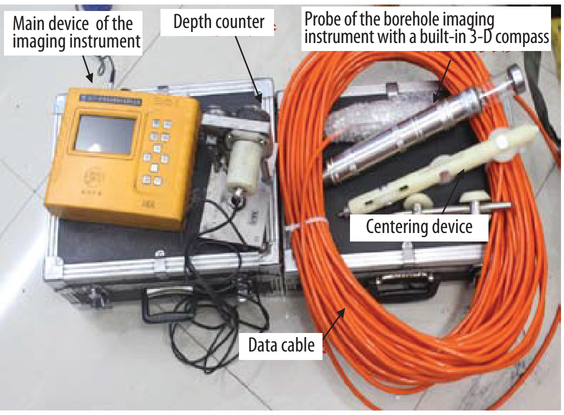


Figure 1. Borehole video instrument

Mining-induced fracture observation

A test was conducted to reveal the evolution pattern of the 3-D fracture network in the coal seam and its overlying rock layer as well as to determine the variation pattern of connectivity as a result of the formation of fractures. Five cross-sections of the coal seam in the Ji-15-14120 roadway at the No. 8 Pingdingshan Coal Mine were selected for observation. Two observation boreholes were drilled on each observation cross-section (one in the coal seam direction and one perpendicular to the roof), and the mining face was situated 100 m behind the cross-sections. Figure 2 shows the actual 3-D arrangement of the observation boreholes and tab. 1 outlines the physical location of each borehole.

Distribution of mining-induced fractures in the field

The borehole detection instrument was used to continuously acquire information on the evolution of fractures on the entire wall of each borehole, from the time the borehole was installed to the time it was destroyed by the mining activities. In addition, an explosion-proof camera was used to record the insertion depth and azimuth of the probe in real time. The distance between each measuring point and the working face was also recorded. Thus, the information of the actual evolution of the 3-D fracture network in the coal rock under mining conditions was obtained.

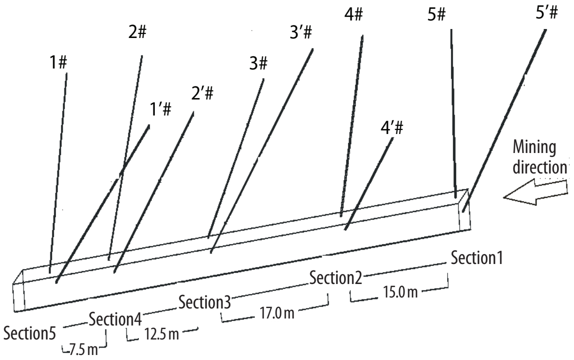


Figure 2. Schematic diagram of the 3-D distribution of the boreholes in the field

Table 1. Physical location of each borehole

	1#	1'#	2#	2'#	3#	3'#	4#	4'#	5#	5'#
Dip angle [°]	70	17	55	20	38	20	52	20	85	22
Length [m]	17	35	21	31	17	35	17	19	17	24

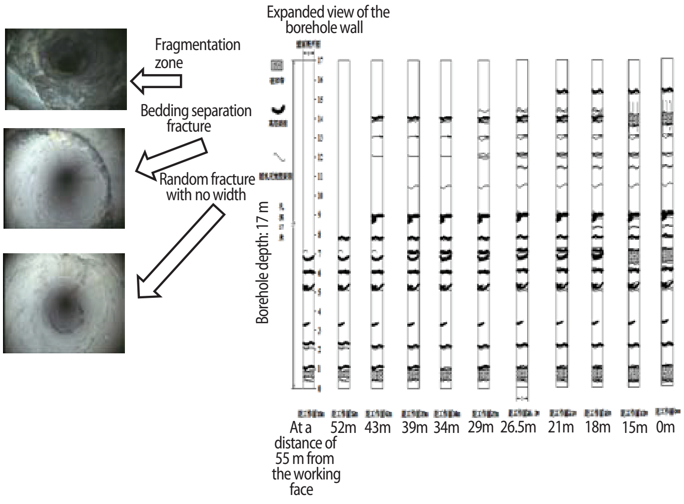


Figure 3. Evolution of the crack network in a roof borehole (section 2)

We will discuss the fracture evolution in the roof borehole located in cross-section 2. Because of the field construction conditions, the dip angle between the axis of the roof borehole and the roof rock layer was different in each roof borehole, resulting in a significant variation in the distribution of fractures in the borehole depth direction. For ease of analysis, the distribution of fractures was projected in the direction perpendicular to the roof. In addition, based on the recorded depth, the video information of the fractures in the borehole wall was vectored using a computer-aided design (CAD) platform and converted to a planar expanded view. Figure 3 shows the evolution of fractures in the roof borehole wall in cross-section 2, obtained from the data processing. The test results show that the mining activity affected the fracture network in the overlying rock layer within approximately 50 m of the mining face. The development of a fracture network in the overlying rock layer outside the mining-affected zone was insignificant as the mining face advanced. The overlying rock layer in the direction perpendicular to the roof can be classified into three zones based on the spatial characteristics of fractures, namely, a fragmentation zone, a nearly-equidistant bedding separation fracture zone, and a random joint zone.

Analysis of the gas migration pattern in mining-induced fractures

In situ mining-induced fracture network extraction theory and method

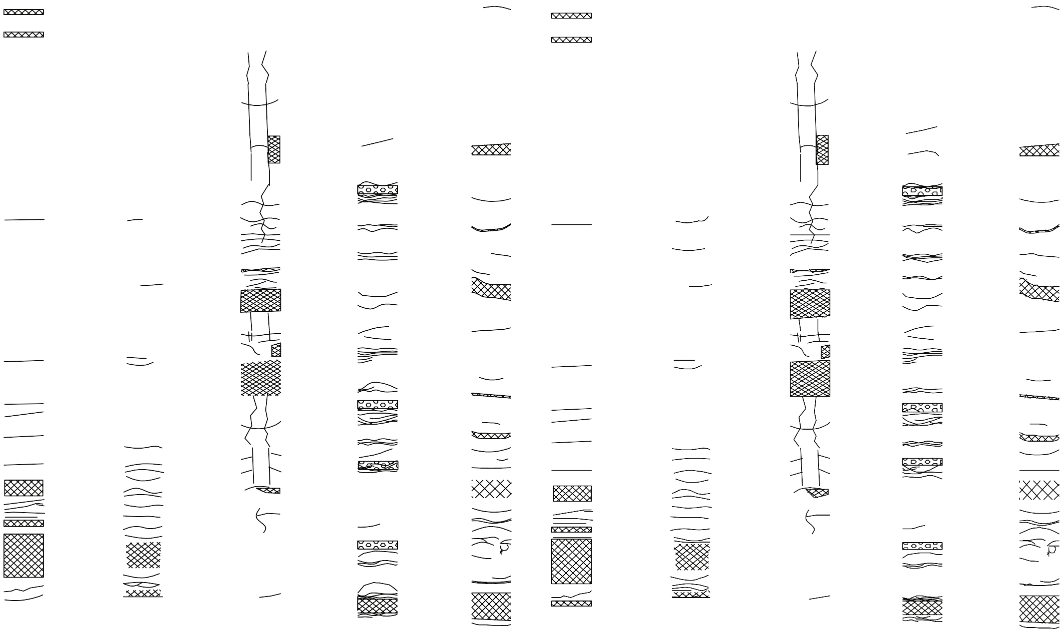
Due to the limitations of the current observation equipment and underground mining conditions, the evolution of a fracture network can only be determined based on an inverse analysis of the spatial evolution of fractures in the walls of boreholes drilled in specific areas.

Data obtained from observations made in the boreholes only covers some of the fractures that exist in the overlying rock. In addition, the angles between the measurement boreholes and the coal seam in the overlying rock can not be controlled to be consistent with one another. It is extremely difficult to obtain information on the distribution of fractures on vertical cross-sections along the mining direction. Using dynamic measurement data to explore the characteristics of the gas-flow in a mining-induced fracture network, it is necessary to make certain assumptions to establish a mining-induced fracture network diagram. Then the gas-flow pattern can be further studied using a numerical simulation platform. Therefore, the following assumptions were made:

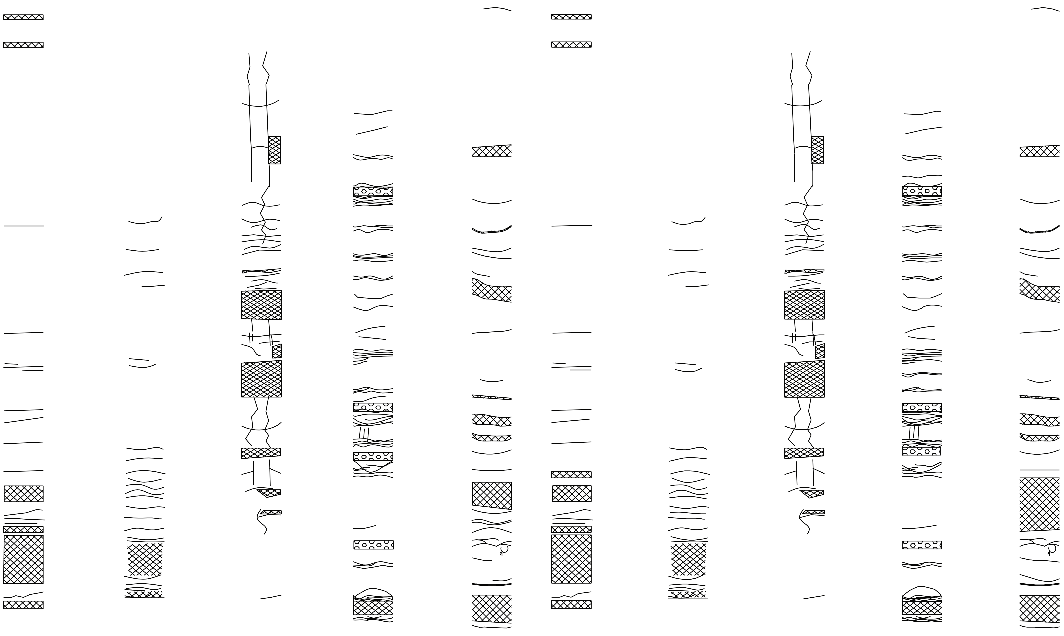
- The gas-flow pattern obtained based on the planar projection of fractures in the walls of the boreholes can represent the characteristics of the gas-flow in the mining-induced fracture network in the roof.
- The spatial morphology of the fractures in the overlying rock exhibits a planar distribution.
- The fragmentation zone in the wall of each borehole is formed as a result of cutting by multiple fractures;

Based on the these assumptions, the video information acquired by the borehole detection instrument in the rock layer was vectored using a CAD platform based on the probe insertion depth and azimuth data recorded by an explosion-proof camera in real time, and the fractures in the boreholes were projected in the direction perpendicular to the roof. Based on the relative spatial distances between the openings of the five boreholes in the overlying rock, planar images of isolated fractures in these boreholes along the mining direction were simultaneously obtained when the boreholes were at various distances from the mining face, figs. 4(a)-4(d). It can be seen that, as the mining face advanced, there was an increase in the number of fractures in each borehole, particularly in the boreholes closer to the mining face, shown on the right side of each image. Based on this information, a model for the gas-flow in the fracture network was established.

A Visual Basic (VB) program was created using the planar CAD vector diagram of the isolated fractures in the five boreholes in the overlying rock along the mining direction, recorded at the same time in boreholes at various distances from the mining face. With this VB program, the co-ordinates of the first and last points of each fracture in each borehole were obtained and then imported into MATLAB. A MATLAB program was used to perform calculations based on the data recorded from each borehole. A linear function was obtained for individual fractures in each borehole and the co-ordinates of the linear function of each fracture in a single borehole in relation to the other boreholes were obtained. Next, a search was made of the data of the fractures in the other boreholes. If there was a match, the two fractures were considered to be matched. After a search was performed of all the fractures in all t boreholes, each unconnected fracture was extended by 3.0 m to the left and right, respectively, in the initial direction. The global co-ordinate data of the connected and unconnected fracture line segments were stored, and a preliminary fracture network image was produced. This image was then imported into CorelDRAW to modify its data type to allow it to be imported into CAD. The fracture network block was then exploded in CAD and the VB program was used to transform all the lines into polylines as well as to modify and seal the network lines and remove the singular boundaries. The fragmentation zones were then superposed on the network image, and multiple fractures were used to represent each fragmentation zone. If the fragmentation zones in two boreholes were approximately in the same line, the fragmentation zones were considered to cut through both boreholes, and thus the multiple fractures representing each fragmentation zone were interconnected. After this process, the boundaries of the 3.0 m thick Ji-15-14120 coal seam and



(a) Reference line was 14.0 m from the mining face (b) Reference line was 11.6 m from the mining face



(c) Reference line was 6.2 m from the mining face (d) Reference line was 3.0 m from the mining face

Figure 4. Fractures in the boreholes when the boreholes were at various distances from the mining face

the corresponding 17 m thick overlying rock layer in the simulation area were drawn. Figure 5 show the fracture network when the reference was 14.0 m from the mining face.

Based on the quasi-continuum model, the mining-induced fractures were considered to be the main channels allowing gas-flow. The rock was viewed as a fractured medium distributed in a certain geometric pattern. By considering the azimuth, density, and aperture of each fracture and the location of the Ji-15 coal seam, the permeability of the fractured rock was determined, which was then used as the basic parameter to establish a model for the gas seepage flow in the fractured rock. The model established in AutoCAD was imported into the gas seepage flow model and substantiated. The model mesh was generated using triangular elements. Figure 6 shows the numerical model for gas-flow in a typical fracture network. The bottom rectangle represents the Ji-15 coal seam. The mining direction is from right to left. The upper part of the model shows the distribution of fractures (composed of the original fractures and mining-induced fractures) in the overlying rock.

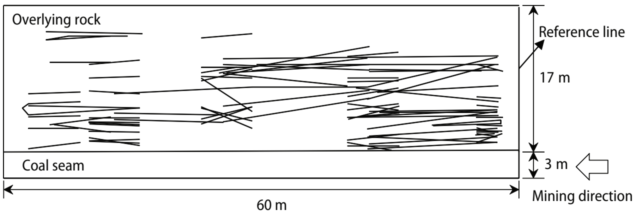


Figure 5. Fracture network when the reference was 14.0 m from the mining face

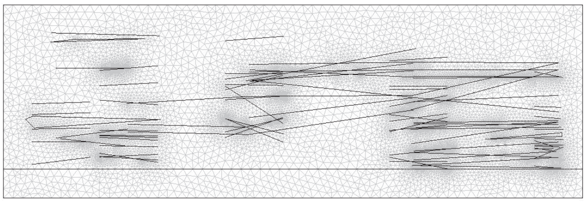


Figure 6. Numerical model for fractures when the reference line is 14.0 m from the mining face

Parameter settings and boundary conditions

The COMSOL numerical analysis software package was used to analyze seepage flow. The basic parameters and boundary conditions for the model calculation are as follows.

- Based on the field data, the basic parameters of the gas, the permeability and storage coefficient of the coal seam, the overlying rock layer and the fractures were obtained, these are given in tab. 2.
- Boundary conditions are given in tab. 3.
- Initial conditions:
  The gas pressure in the coal seam was set to an initial value.

Table 2. The calculation parameter

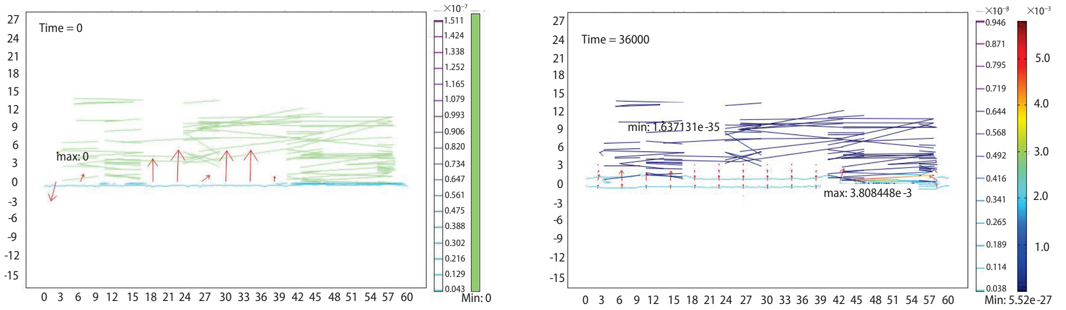
Parameters of the gas		Permeability [m^2]			Storage factor		
Density [kgm^{-3}]	Dynamic viscosity [Pa s]	Coal seam	Rock	Fractures	Coal seam	Rock	Fractures
1.35	1.34E–5	2.89E–20	8.00E–21	3.00E–9	2.89E–20	8.00E–21	3.00E–9

Gas-flow pattern simulation

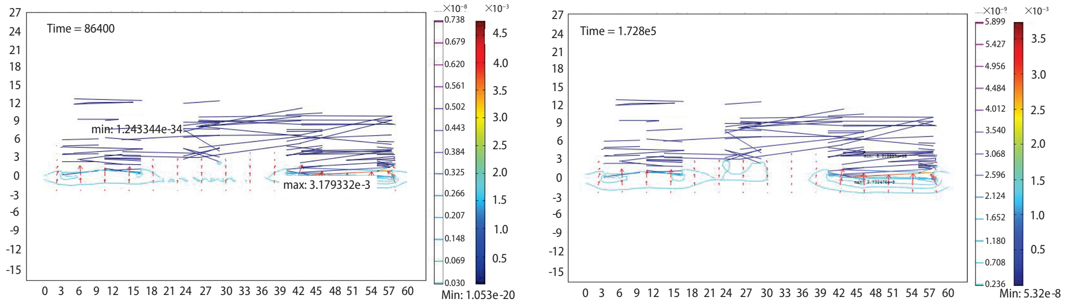
Figures 7(a)-7(d) shows the gas--flow rate distribution at different times when the reference line is 14 m from the mining face.

Table 3. Pressure boundary parameters

Initial gas pressure of the Ji-15 coal seam [MPa]	Residual gas pressure in the goaf region [MPa]
1.6	0.15



(a) Gas flow rate distribution at 0 h (b) Gas flow rate distribution at 10 h



(c) Gas flow rate distribution at 1 day (d) Gas flow rate distribution at 2 day

Figure 7. Simulated gas-flow in the fractures at different times, showing the whole-field gas-flow contour lines when the reference line is 14 m from the mining face
(*for color image see journal web site*)

This indicates that: the gas migrates to another region via the fractures, the fractures play an important role in reducing the coal pressure, and the fractures are the main channels for gas migration. The gas-migration-rate distribution at various times shows that the initial-gas-seepage flow-rate contour lines are basically parallel to the coal rock layer. As the mining face advances, the gas migrates further into the rock. The fractures in the rock affect the gas-flow pattern. The gas-flow rate contour lines mainly swirl around the fracture zones, and the gas-flows to where the fractures are more developed. The gas-flow rate vectors point to the densely fractured zones. Thus, it can be concluded that the gas in the coal rock near the fractures mainly migrates to the denser fracture zones, and the fractures provide the main channels for gas-flow. The gas-flow rates in the fractures are far higher than those in the coal rock.

Conclusions and suggestions

In this work, a full-parameter fracture observation instrument was developed, and a dynamic fracture observation technique was proposed. A field fracture observation test was conducted for three months to obtain information on fracture networks under actual mining conditions. It was found that the variation of the fractal dimension of fractures in the wall of a borehole had three stages as the mining face advanced, namely, a stable stage, an increasing stage and a stable stage. Overall, the fractal dimension of the fractures in the wall of each borehole increased as the mining face advanced.

The video information of the fractures in the borehole walls was vectored on a CAD platform and converted to 2-D expanded images. In addition, the probe insertion depth and azimuth data recorded in real time were also vectored, based on the fractures in the borehole walls that were projected in the direction perpendicular to the roof. Using the relative spatial distances between the openings of the boreholes, planar images of isolated fractures in the mining direction were obtained when the boreholes were at various distances from the mining face. A 3-D fracture network was established based on this information. The gas migration pattern was calculated using the COMSOL computation platform.

Between the start of the monitoring and 10 houres, there was a decrease in the gas pressure in the coal, but this was limited in magnitude and occurred within a relatively small area. The gas-flow rate contour lines were also affected by the initial pressure distribution in the coal and the coal seam. During this 10 hour period, the gas-flow rate contour lines exhibited a trend to move toward the fractures, which mainly occur parallel to the coal seam. This gas-flow direction was also for the most part parallel to the coal seam. Therefore, between the start of the monitoring and 10 houres, the gas-flow is mainly controlled by the coal seam, this stage is referred to as the coal seam control stage. Between 10 houres and 1 day, the gas pressure in the coal decreased by a relatively large magnitude over a fairly large area. During this time, the gas-flow rate contour lines gradually shifted from parallel to the contact surface with the coal rock to parallel to the fractures, and the gas-flow direction also gradually changed from perpendicular to the contact surface to perpendicular to the fractures. Therefore, between 10 houres and 1 day, the fractures began to affect the gas-flow and the main factor controlling the gas-flow moves from the coal seam to the fractures. This stage is referred to as the fracture effect formation stage. After 1 day, the gas pressure in the coal decreased rapidly with a subsequent rapid decline in the coal pressure. During this time period, the gas-flow rate contour lines and the gas-flow direction underwent changes in some areas but overall they remained consistent with the distribution patterns seen at approximately 1 day. This indicates that after approximately one day, the factures completely control the gas-flow. This stage is referred to as the fracture control stage.

In summary, when fractures are present, the gas in a coal rock can more easily migrate to surrounding rocks or extraction tunnels situated relatively far away from the coal seam. Since gas-flows faster in fractures, the presence of fractures can accelerate the depressurization of gas in coal seam and lead to a more pronounced depressurization efficiency. Therefore, in practice, fractures formed during the mining process can be used to decrease the gas pressure in the coal bed. On the other hand, based on the engineering need, fractures can be artificially produced to more efficiently decrease the gas pressure. That is, artificial fracturing can be performed to improve the gas extraction efficiency and to ensure safety at the working mine face.

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