# FRACTURE EVOLUTION AND GAS TRANSPORT LAWS OF COAL AND ROCK IN ONEKILOMETER DEEP COAL MINE WITH COMPLICATED CONDITIONS

by

***Jianguo ZHANG[a,b], Man WANG[a,b*], Yingwei WANG[a,b]***

[a] State Key Laboratory of Coking Coal Exploitation and Comprehensive Utilization, Pingdingshan, China
[b] China PingmeiShenma Group, Pingdingshan, PR China

*As coal mining gradually extends deeper, coal seams in China generally show high stress, high gas pressure and low permeability, bringing more difficulty to coal mining. Therefore, in order to strengthen gas extraction, it is necessary to carry out reservoir reconstruction after deep coal seams reached. In this paper, the distribution and evolution laws of fracture zone overlaying strata of J15 seam in Pingdingshan No. 10 coal mine after excavation were studied by combining similar simulation and numerical simulation, meanwhile, the gas transport law within fracture zone was numerically simulated. The results show that the fracture zone reaches a maximum of 350 mm in the vertical direction and is 75 mm away from W9,10 coal seams in vertical distance. Since W9,10 coal seams are in an area greatly affected by the bending zone of J15 coal seam under the influence of mining, the mining of J15 coal seam will exert a strong permeability enhancement effect on W9,10 coal seams. J15 coal seam can act as a long-distance protective layer of W9,10 coal seams to eliminate the outburst danger of the long-distance coal seams in bending zone with coal and gas outburst danger, thereby achieving safe, productive and efficient integrated mining of coal and gas resources. The gas flux of mining-induced fractures in the trapezoidal stage of mining-induced fracture field is far greater than that in the overlaying stratum matrix. The horizontal separation fractures and vertical broken fractures within the mining-induced fracture field act as passages for gas flow. Compared with gas transport in the overlaying stratum matrix, the horizontal separation fractures and vertical broken fractures within the mining-induced fracture field play a role in guiding gas flow. The research results can provide theoretical support for the arrangement of high-level gas extraction boreholes in roof fracture zones*

.

Key words: *over kilometer deep coal mine; fracture zone; gas transport*

## Introduction

As coal mining gradually extends deeper, coal seams in China generally show high stress, high

* Corresponding author; e-mail: wangman.w@gmail.com

gas pressure and low permeability, bringing more difficulty to coal mining [1-3]. Therefore, with the deepening of coal mining, pressure-relieved mining in coal seams and fracture reconstruction of coal reservoirs must be taken into consideration for coal mine gas extraction in China[4,5]. The protective layer mining technology has widely proven to be the most effective gas extraction and treatment technology under the coal seam group conditions [1,6,7].

The mining of coal seam will bring about a pressure relief and permeability enhancement effect. That is, it will cause a decrease in geostress of surrounding rock layer as well as the growth and interconnection of pores and fractures. For example, after No. 2 coal seam of Sichuan Tianfu south mine are mined, the permeability of No. 9 seam which is 80 m beneath it increases by 500 times. Then, when No. 7 seam which is 24 m above No. 9 seam is mined, its permeability increases by 50,000 times, which provides a good condition for gas extraction [8]. Currently, domestic and foreign scholars have conducted a large number of researches on the gas transport law in the mining-induced fracture field above goaf. Through model experiment, image analysis and discrete element simulation and based on the key layer theory of rock formation control, Qian and Xu[9,10] put forward that the mining-induced fractures of overlaying strata developed in two stages and distributed in an “O-shape” circle after coal mining. Based on the theory of mining-induced fracture “O-shape” circle, Lin et al.[11] proposed a project simplified model of mining-induced fracture rounded rectangular ladder belt and analyzed the dynamic evolution process by combining physical similar material simulation experiments. Gao et al. [12] combined their results with the critical quantitative index to investigate the abutment pressure, degree of complexity of the mining induced fracture network, and the evolutionary trend of connectivity under the high discharge condition, and found the abutment pressure response lags behind the response of the characteristic values (fractal dimension and connectivity) as the mining-induced fractures evolve. Aiming at solving technical problems existing in the safe and efficient mining of coal seams with low permeability, high adsorption and high gas, Yuan [6] studied scientific laws such as the rock stratum movement and stress distribution within pressure-relieved mining stope, the evolution of fracture field, the pressure-relieved gas enrichment area and the transport law, explored gas extraction in pressure-relieved mining and established a technical system of integrated coal production and gas extraction by taking Huainan mining area as the main experimental research base and employing theories such as stratum movement, “O-shape” circle and gas flow. His findings solved the major engineering and technical problem of integrated coal production and gas extraction.

From the point of view of pressure-relieved gas flow channel, the fracture-forming effect of mining-induced damage results in the formation of three zones in the vertical direction above goaf. In terms of pressure-relieved gas flow, the action of rock caving and the supporting and compaction effect of natural filling also results in the formation of three zones in the lateral direction above goaf. They are the normal stress zone (enhanced permeability and flow zone under initial pressure relief), the stress relief zone (high permeability and flow zone under full pressure relief) and the recompacting zone (reduced permeability and flow zone under recovered geostress) respectively, three of which all exist within the caving zone and bending zone in the vertical direction. The zoning model of mining effects formed in overlaying strata by coal seam mining is shown in Fig. 1 [13-16].

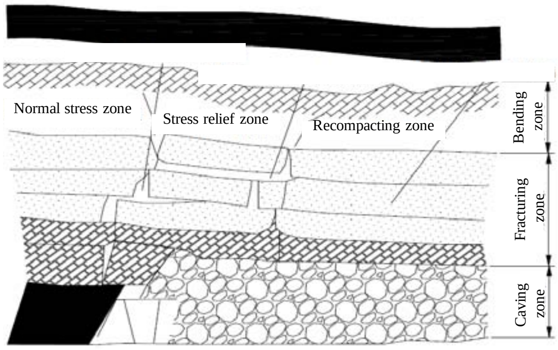



Fig. 1 Distribution of three vertical zones and three lateral zones of overlaying strata in stope

Although lots of researches have been studying on the strengthening of coal seam gas extraction through protective layer mining, the dynamic evolution law of fracture zone in the overlaying strata in stope and its influence on the evolution and distribution laws of gas flow filed within the fracture zone are still unknown. These problems lead to the blind layout of high-level boreholes which are used to treat gas within the fracture zone in the coal mine field, resulting in a poor effect of gas extraction from boreholes.

In order to solve the above problems, this paper studied the dynamic evolution law of fracture zone in the overlaying strata during the coal mining process by performing a similar simulation test under the laboratory conditions. Meanwhile, we studied the evolution and distribution laws of gas flow field in the fracture zone by adopting the numerical simulation method. The research results can provide theoretical basis for gas control at coal mine sites.

## Overview of test site

Belonging to China Pingmei Energy and Chemical Group, No. 10 mine of PingdingshanTian'an Coal Mining Corp. Ltd. is located in the eastern part of Pingdingshan City, Henan Province, China and is about 6 km far from the city center. With a coal bearing area of 31.5 km$^2$, it is 5.6 km long in east-west direction and 7.0 km wide in north-south direction.

The mine is developed comprehensively through multi-level vertical and inclined shafts. There are three production levels, among which Level 1 with an elevation of -140 m has basically finished its recovery; Level 2 with an elevation of -320 m is the main mine production level; and Level 3 with an elevation of -800 m is under construction.

In July 2011, No. 10 mine was approved as a coal and gas outburst mine by Industry and Information Technology Department of Henan Province, as its relative and absolute gas emission rates are 21.57 m/t and 112.09 m/min respectively and its relative and absolute $CO_2$ emission rates are 11.14 m/t and 57.9 m/min respectively. The three major mining groups, Group D, Group W and Group J, are all outburst coal seams that have undergone outbursts for 50 times in history.

The research object of this study is $J_{15\text{-}17200}$ working face and the No. 9 and No. 10 coal seams located 170 m above it. The coal seam occurrence of $J_{15\text{-}17200}$ working face is relatively stable. The normal coal seam is the primary structural coal whose failure type mostly belongs to Types I and II and partly belongs to Type III. The coal seam joint is relatively developed, and the roof and floor of coal seam are dark grey sandy mudstone and black mudstone respectively with poor permeability. Its thicknesses lie in the range of 0.1~6.5 m with an average of 3.15 m, and the dip angles lie in the range of 10~40° with an average of 19°. With a mining length of 225.3 m and a recoverable reserve of 673,000 t, it has a strike length of 762.5 m, a working face elevation of -483.167~-565.31 m and a vertical depth of 658.48~785.31 m. The original gas pressure is 2.6 MPa, and the original coal seam gas content is 15.256 $m^3$/t.

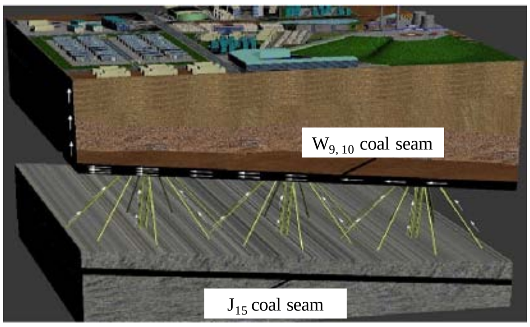



Fig. 2 Spatial distribution structure of coal seams [17]

Adopting U-shaped ventilation, $J_{15-17200}$ working face has an air flow of 1800 $m^3$/min. Gas and CO sensors are installed in the intake airway and return airway in accordance with the regulations. A set of compressed-air self-rescue equipment is arranged every 50 m. The spatial distribution structure of coal seams is shown in Fig. 2.

## Fracture evolution law in stope

In order to study the evolution law of fracture zone in the overlaying strata during the mining process of $Y_{15-17200}$ working face as well as its influence on the overlaying $W_{9,10}$ coal seams, this paper researched on the laws of rock breakage, fracture evolution and distribution as well as stratum deformation and displacement adopting the method of similar simulation, which lay the foundation for later studies on the evolution of gas flow field.

### *Introduction to experimental model and system*

According to the comprehensive geological histogram of Pingdingshan No. 10 mine, the similarity simulation method was used to simulate the fracture evolution law of overlaying strata during coal mining. Fig. 3a shows a physical map of the similar model, in which the colors of strata are primarily to distinguish between different lithology. Table 1 lists the basic parameters and material ratios of different strata. The geometric similarity ratio between the model and the real strata is 1: 400.

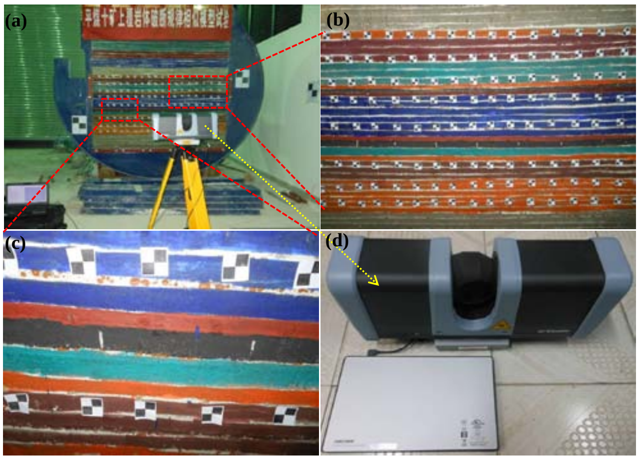



Fig. 3 Experimental model and system (a) Experimental system; (b) Displacement measuring point; (c) Quasi mining seam; (d) Trimble FX three-dimensional laser scanner

The deformation law of overlaying strata during mining process should be checked during the experiment. For this purpose, in the study area, a displacement monitoring line was arranged every 10 cm, and each monitoring line was equipped with a monitoring point every 10 cm, as shown in Fig. 3 (b).

Trimble FX three-dimensional laser scanner shown in Fig. 3 (d) was used to scan the strata before and after mining, through which the three-dimensional coordinates of strata under different conditions can be obtained. The scanned data were imported into Trimble Real-works post-processing software to form point cloud data.

A complete similar simulation model test mainly includes six steps. The specific test procedures are as follows:

(1) Fine river sand was selected as aggregate; gypsum and calcium carbonate as binders; and cement, cork and oil as seasoning. The fine sand was dried and screened before the test.

(2) The similar material ratio test was carried out to find the ratio in line with the mechanical parameters of prototype material.

(3) According to the selected ratio, the material was stacked on a similar simulation test stand. The stack was done layer by layer, and mica powder was sprinkled between layers to better simulate the real condition.

(4) During the pre-mining of each layer stack, the coal seams were covered with plastic film in addition to the separation layer made up of mica, so that the coal seam can be mined conveniently and quickly in the later excavation stage.

(5) The dried similar model was mined from left to right for 80 cm (20 cm in the model) each step, and the mining was divided into 6 steps.

(6) Before each step of mining, the model was thoroughly scanned by a three-dimensional laser scanner. Then, it was scanned after 180 min at the completion of mining. The next step of mining started after it was completely stabilized.

Table 1 Material ratios of different strata

| No. | Strata | Real thickness /m | Model thickness /m | Tensile strength /MPa | Ratio (sand: paste: calcium) |
|---|---|---|---|---|---|
| 1 | Medium to coarse sandstone | 309.4 | 0.7735 | 70.6 | 5:6:4 |
| 2 | Sandy mudstone | 3.6 | 0.009 | 42.4 | 8:7:3 |
| 3 | Coal | 4 | 0.01 | 21 | 10:6:4 |
| 4 | Sandy mudstone | 5 | 0.0125 | 42.4 | 8:7:3 |
| 5 | Medium to coarse sandstone | 83.1 | 0.20775 | 70.6 | 5:6:4 |
| 6 | Mudstone | 5.4 | 0.0135 | 39 | 9:7:3 |
| 7 | Coal | 10.5 | 0.02625 | 21 | 10:6:4 |
| 8 | Sandy mudstone | 7.1 | 0.01775 | 42.4 | 8:7:3 |
| 9 | Sandy mudstone | 3.77 | 0.009425 | 42.4 | 7:7:3 |
| 10 | Mudstone | 175 | 0.4375 | 70.6 | 5:6:4 |
| 11 | Sandy mudstone | 5.94 | 0.01485 | 42.4 | 8:7:3 |
| 12 | Mudstone | 2.43 | 0.006075 | 39 | 9:7:3 |
| 13 | Coal | 4 | 0.01 | 21 | 10:6:4 |
| 14 | Fine sandstone | 11 | 0.0275 | 49.7 | 7:7:3 |
| 15 | Coal | 2 | 0.005 | 21 | 10:6:4 |

*Experimental results and analysis*

Six steps of mining were carried out in the experiment with a mining distance of 80 m (20 cm in the model) for each step. Fig. 4 shows the results of the 2nd, 4th, 5th and 6th mining steps are given here.

When the coal seam is mined for 160 m, the upward inclined macro main cracks generated at the tip of both wings continue to expand. The direct roof of mining area caves and the central part of direct roof fractures obviously. Meanwhile, the overlaying soft rock forms a new direct roof. The angles between fractures and vertical principal stress become smaller. That is, the fractures further develop in the direction of maximum principal stress. The primary fractures further develop, expand and interconnect to form new secondary cracks. Strata near the roof have a bending trend, and a certain number of micro cracks are formed in their middle part. With the increasing scope of mining influence, these micro cracks can be observed in the main roof. As can be seen from the three-dimensional laser scanning data, the caving zone continues to expand upward after the 2nd step, and the direct roof also caves on the caving basis of the 1st step.

When the coal seam is mined for 320 m, the layer separation phenomenon of direct roof gets more and more obvious, which results in a concaving shape in the central part. A trapezoid-resembling shape appears in the overall distribution of fractures. The caved roof is compacted again, and criss-cross cracks are generated in the main roof. A separation layer is formed at the floor of the protected layer. Compared with the 2nd step, this step witnesses a larger expansion of fracture zone both laterally and vertically.

When the coal seam is mined for 400 m, the layer separation phenomenon of main roof gets even serious. The downward displacement of each layer becomes larger and larger until the layers cave to fill the goaf.

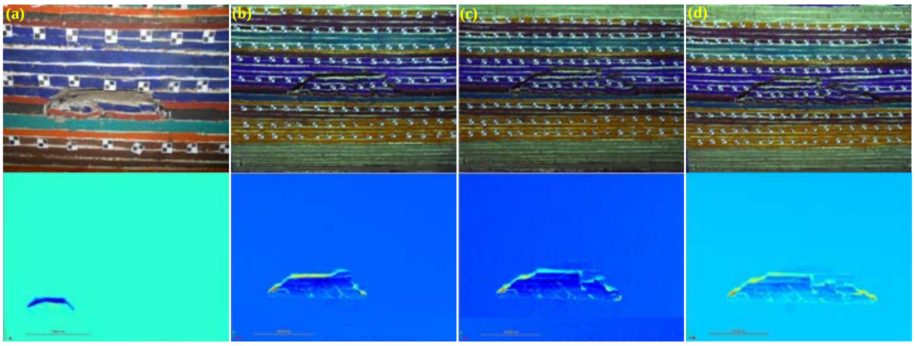



Fig. 4 Fracture evolution of overlaying strata during coal seam mining

(a) Mining for 160 m; (b) Mining for 320m; (c) Mining for 400m; (d) Mining for 480m

After the excavation, the displacement of each measuring point on No. 4 and No. 5 measuring lines is measured, and the curve obtained is shown as shown in Fig. 5.

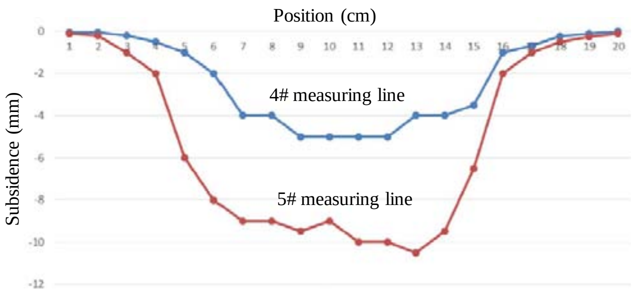



Fig. 5 Roof subsidence curve

The measuring points of No. 5 measuring line are arranged in the roof of the excavated coal seam. It can be known from the curves in Fig. 5 that under the influence of mining, the rock strata above coal seam start to deform at 30 m to 40 m ahead of the mining face. It is characterized by intense horizontal displacement and small vertical displacement. When the advance of working face through this area causes a sharp increase in vertical displacement, the measuring point in the middle of the goaf reaches its maximum displacement of 10.5mm (4.2m in reality). The fracture distribution of pressure arch shows a more and more evident trapezoid shape. Under the action of vertical stress, the broken rock mass keeps fracturing, caving and filling to the goaf, and then it is continuously compacted. When the mining advances to the 6$^{th}$ step, 120 cm (480 m in reality) has been excavated. As can be observed from the three-dimensional laser scanner displacement cloud, the fracture zone reaches a maximum of 350 mm (140 m in reality) in the vertical direction and is 75 mm away from $W_{9,10}$ coal seams in vertical distance (30 m in reality) which is a short distance. Since $W_{9,10}$ coal seams are in an area greatly affected by the bending zone of $J_{15}$ coal seam under the influence of mining, the mining of $J_{15}$ coal seam will exert a strong permeability enhancement effect on $W_{9,10}$ coal seam. From the results of similar model experiments, $J_{15}$ coal seam can act as a long-distance protective layer of $W_{9,10}$ coal seams to eliminate the outburst danger of the long-distance coal seams in bending zone with coal and gas outburst danger.

## Gas transport law in stope

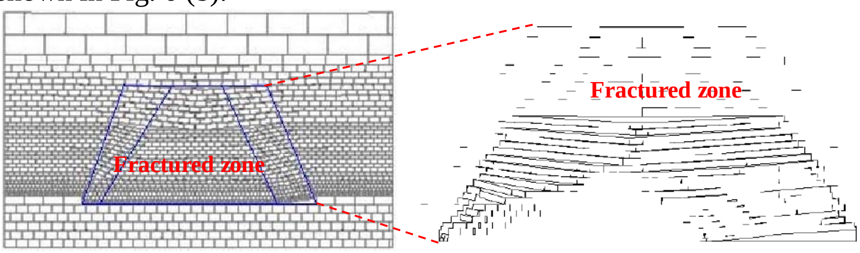
In order to find out the gas transport law within the mining-induced fracture zone, this section is to study the gas enrichment law and flow process within the fracture zone adopting numerical simulation method. The goal is to provide theoretical basis for the layout of high-level boreholes [14,18-20].

### *Modeling of mining frature zone*

When studying the gas transport law of fracture field, this paper carried out relevant research work through combining UDEC software with COMSOL software. UDEC software was used to simulate the evolution of fracture field in the mining process first, and then the results were imported into COMSOL software to simulate the transport of gas.

In order to simulate the gas transport process in the mining-induced fracture field, the fracture field obtained by UDEC was processed into a spatial form diagram by means of image processing method and imported into COMSOL as the fracture field model. In this way, both software can be taken full of advantage of and combined with each other.

Fig. 6 (a) shows the form of mining-induced fracture field obtained by UDEC numerical simulation. The fracture field blocks were colored, and then fractures in the mining-induced fracture field were extracted using CORE DRAW software. The fracture distribution in the mining-induced fracture field is shown in Fig. 6 (b).




(a) (b)

Fig. 6 Distribution law of mining-induced fracture field

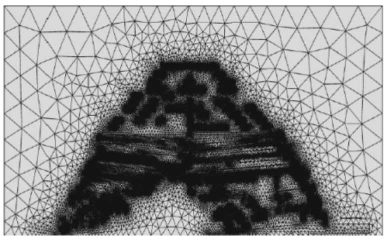


Fig. 7 Mesh generation after the import of fractures

The fractures in the mining-induced fracture field extracted were imported into COMSOL numerical simulation software. Meanwhile, its model was meshed in a total of 211,583 units. As shown in Fig. 7, the fracture area was specially refined.

*Evolution of gas flow field in the mining area*

Fig. 8 shows the dynamic evolution law of coal seam gas transport in the mining-induced fracture field at different moments. Gas flux is larger in the area with a larger separation layer of overlaying strata in the trapezoidal stage of mining-induced fracture field. In Fig. 8, the size of the arrows represents the size of gas flux. It is clear that the gas flux of mining-induced fractures in the trapezoidal stage of mining-induced fracture field is far greater than that in the overlaying stratum matrix. The horizontal separation fractures and vertical broken fractures within the mining-induced fracture field act as passages for gas flow. Moreover, with gas transport in the trapezoidal stage of mining-induced fracture field, gas enrichment area is basically located at the area with the largest separation fracture at the top of mining trapezoidal stage.

At the initial moment (200 s), gas mainly concentrates in the gas source and spreads all around through the pores of coal matrix. The more developed the fractures, the larger the gas flux. When the gas gradually fills the entire fissure zone, it spreads all around mainly through the coal matrix in a significantly reduced speed.

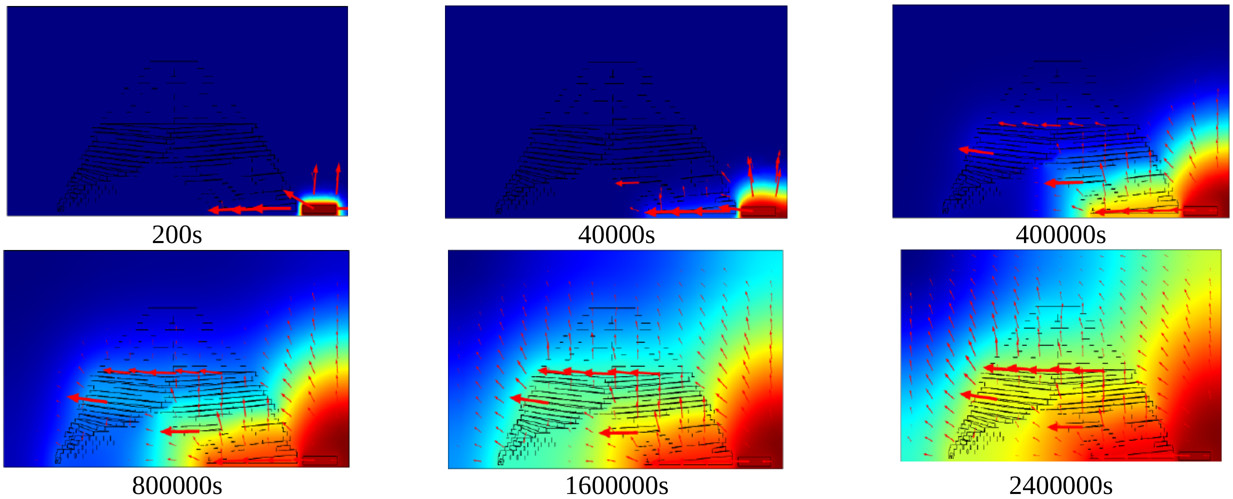


Fig. 8 Evolution of gas flow field in mining-induced fracture zone

**Conclusions**

Aiming at solving the problem of unclear fracture evolution and gas transport laws within overlaying strata, this paper carried out relevant similar simulation and numerical simulation experiments, discussed the fracture zone distribution and evolution laws of the overlaying strata during the coal mining and simulated the gas transport process in the fracture zone. The conclusions are drawn as follows.

From the results of the similar model, the fracture zone reaches a maximum of 350 mm (140 m in reality) in the vertical direction and is 75 mm away from $W_{9,10}$ coal seams in vertical distance (30 m in reality) which is a short distance. Since $W_{9,10}$ coal seams are in an area greatly affected by the bending zone of $J_{15}$ coal seam under the influence of mining, the mining of $J_{15}$ coal seam will exert a strong permeability enhancement effect on $W_{9,10}$ coal seam.

The mining of lower coal seam has a certain pressure relief and permeability enhancement effect on the upper Group W coal seams and can promote the gas extraction of Group W coal seams. $J_{15}$ coal seam can act as a long-distance protective layer of $W_{9,10}$ coal seams to eliminate the outburst danger of the long-distance coal seams in bending zone with coal and gas outburst danger.

Numerical simulation results show that the gas flux of mining-induced fractures in the trapezoidal stage of mining-induced fracture field is far greater than that in the overlaying stratum matrix. The horizontal separation fractures and vertical broken fractures within the mining-induced fracture field act as passages for gas flow. Compared with gas transport in the overlaying stratum matrix, the horizontal separation fractures and vertical broken fractures within the mining-induced fracture field play a role in guiding gas flow.

## Acknowledgements

This work was financially supported by the State Key Research Development Program of China (Grant No. 2016YFC0600700).

## References

[1] Liu T., *et al.*, An Integrated Technology for Gas Control and Green Mining in Deep Mines Based on Ultra-Thin Seam Mining, *Environmental Earth Sciences*, 76(2017), 6, pp.243

[2] Xie H.B., *et al.*, Research and Consideration of Deep Coal Mining and Critical Mining Depth, *Journal of China Coal Society*, 37(2012),37, pp.535-542

[3] Liu X.F., *et al.*, Effects of Gas Pressure on Bursting Liability of Coal Under Uniaxial Conditions, *Journal of Natural Gas Science and Engineering*, 39(2017), Jan., pp. 90-100

[4] Liu T., *et al.*, Influence of Coupled Effect Among Flaw Parameters on Strength Characteristic of Precracked Specimen: Application of Response Surface Methodology and Fractal Method, *Journal of Natural Gas Science and Engineering*, 26(2015), 9, pp. 857-866

[5] Liu T., *et al.*, Investigation on Mechanical Properties and Damage Evolution of Coal After Hydraulic Slotting, *Journal of Natural Gas Science and Engineering*, 24(2015), Apr., pp. 489-499

[6] Yuan L., The Theory of Pressure Relieved Gas Extraction and Technique System of Integrated Coal Production and Gas Extraction, *Journal of China Coal Society*, 01(2009), Jan., pp. 1-8

[7] Yuan L., Xue S., Defining Outburst-Free Zones in Protective Mining With Seam Gas Content-Method and Application, *Journal of China Coal Society*, 39(2014), 09, pp. 1786-1791

[8] Li W., Study on Mechanical Characteristics of Coal and Rock and Gas Migration Law Under the Influence of Mining, *Chongqing University*, 2014

[9] Qian M.G., Xu J.L., Study on the "O-Shape" Circle Distribution Characteristics of Mining-Induced Fractures in the Overlaying Strata, *Journal of China Coal Society*, 05(1998), pp. 20-23

[10] Xu J.L., Qian M.G., Study and Application of Mining-Induced Fracture Distribution in Green Mining, *Journal of China University of Mining & Technology*, 02(2004), pp. 17-20

[11] Lin H., *et al.*, Experimental Analysis of Dynamic Evolution Model of Mining-Induced Fissure Zone in Overlaying Strata, *Journal of Mining & Safety Engineering*,02(2011), pp. 298-303

[12] Gao, M.Z., *et al.*, Field Experiments on Fracture Evolution and Correlations Between Connectivity and Abutment Pressure Under Top Coal Caving Conditions. *International Journal of Rock Mechanics and Mining Science*, 111(2018), Oct., pp. 84-93

[13] Zhang C., *et al.*, Evaluating Pressure-Relief Mining Performances Based on Surface Gas Venthole Extraction Data in Longwall Coal Mines, *Journal of Natural Gas Science and Engineering*, 24(2015),

Apr., pp. 431-440
[14] Wang L., *et al.*, Fracture Evolution and Pressure Relief Gas Drainage from Distant Protected Coal Seams Under an Extremely Thick Key Stratum, *Journal of China University of Mining & Technology*, 18(2008), 2, pp. 182-186
[15] Yin G., *et al.*, Mechanical Behavior and Permeability Evolution of Gas Infiltrated Coals during Protective Layer Mining, *International Journal of Rock Mechanics and Mining Sciences*, 80(2015), Aug., 292-301
[16] Sang S., *et al.*, Stress Relief Coalbed Methane Drainage by Surface Vertical Wells in China, *International Journal of Coal Geology*, 82(2010), 3-4, pp. 196-203
[17] Zhang D., *et al.*, Coal and Rock Fissure Evolution and Distribution Characteristics of Multi-Seam Mining, *International Journal of Mining Science and Technology*, 23(2013), 6, pp. 835-840
[18] Yin W., *et al.*, Mechanical Analysis of Effective Pressure Relief Protection Range of Upper Protective Seam Mining, *International Journal of Mining Science and Technology*, 27(2017), 3, pp. 537-543
[19] Yang W., *et al.*, Stress Evolution with Time and Space During Mining of a Coal Seam, *International Journal of Rock Mechanics and Mining Sciences*, 48(2011), 7, pp. 1145-1152
[20] Liu T., Lin B.Q., Yang W., Impact of Matrix-Fracture Interactions on Coal Permeability: Model Development and Analysis, *Fuel*, 207(2017), Jun., pp. 522-532

Paper submitted: May 26, 2018
Paper revised: June 21, 2018
Paper accepted: November 15, 2018