Effect of roof movement on gas flow in an extremely thick coal seam under fully mechanized sublevel caving mining conditions

Haijun Guo1,2 | Xianzhang Li1 | Hao Cui1 | Kaixuan Chen1 | Yuanyuan Zhang1

1School of Emergency Management and Safety Engineering, China University of Mining and Technology, Beijing, China
2State Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, Jiaozuo, China

Abstract
The abnormal emission of gas in coals is the main factor that induces serious gas disasters in coal mines. During the coal mining process, roof movement has important effects on the gas emission law and gas flow characteristics. In this study, an extremely thick coal seam under fully mechanized sublevel caving mining conditions from the Tashan coal mine in China was used as an example; the effect of roof weighting on gas emission in the goaf was studied. Then, the large roof weighting step and the small roof weighting step caused by the different thicknesses of lamprophyre breakage were used as the objects and a numerical simulation study on the gas flow characteristics in the goaf was carried out. The results indicate that the mining coal seams, the overlying adjacent unmined coal seams, and the goaf are the main contributors to the large gas emission capacity, and even situations exist where the gas concentration exceeds the limit in the working face. During roof weighting, the gas concentration and emission capacity in the return airway, upper corner, and high drainage roadway increase substantially. The results of the numerical analysis are in good agreement with the observed data, which indicates that it is effective to control the gas in coal seams by designing the location of high drainage roadway according to the mining characteristics of coal seam and the gas emission law.

KEYWORDS
extremely thick coal seam, gas emission, goaf, hard roof, roof weighting

1 | INTRODUCTION

Coal, which is the major energy supply in China, plays a leading role in serving the country’s economic development.1–3 In China, most of the coal resources are buried deep underground. The original coal seam, the surrounding rock, and the coalbed methane constitute an equilibrium system that existed before the coal seam was mined.4–7 When coal mining is carried out, the overlying strata are damaged and collapse, which results in the formation of a curve subsidence zone, fracture zone, and caving zone.8–10 During the coal mining process, the coal body in front of the working face undergoes the process of first being pressurized and then depressurized.11–13 Moreover, the expansion of original cracks and the formation of new cracks in coal also occur, which results in a sharp increase in coal permeability. As a result, the gas in coal desorbs rapidly, and sometimes, it can lead to abnormal gas emissions, which results in serious disasters, such as gas explosions or coal and gas outbursts (“outbursts” for short).14–17 Furthermore, after a coal seam is mined, the fallen rocks stack disorderly in the goaf with a large loose coefficient, which results in the gas flowing into the goaf along the...
cracks. The difference in the gas concentration between
the goaf and the working face results in gas convection in the
goaf and in the working face until the new dynamic equilib-
rium is reached.

In China, the investigation on the gas seepage law in
coals has a history of more than 50 years, with various the-
ories that have played important roles in ensuring the safe
production of coal mines. From the perspective of seepage
mechanics, Zhou et al combined outbursts with single-medium models to the complex dual-porosity
include shifts from single-phase flow to multiphase flow and
press from theory to application. The main achievements in-
son gas flow in fractured fields has made considerable prog-
res.

Currently, because of the improvement of experimental
methods and numerical calculating techniques, the study
on gas flow in fractured fields has made considerable prog-
ress from theory to application. The main achievements in-
clude shifts from single-phase flow to multiphase flow and
from single-medium models to the complex dual-porosity
structure models. Zhou and He combined outbursts with
geostructural factors and proposed the rheological
hypothesis of the outburst mechanism that is influenced by
stress fields, which reveals the gas flow characteristics in coal
seams from the perspective of “solid-gas” coupling. Xue et al introduced the percolation theory for the development of
mining-induced cracks, established the percolation model of
the overlying strata, and obtained a relationship between the
percolation characteristics and the periodic roof weighting.
Xu et al studied the fatigue properties of the rock mass with
intermittent cracks and found that fatigue deformation was
affected by the loading frequency, the load level, and the geo-
metrical position of intermittent cracks. With respect to the
intuitionistic description of the development of cracks in coal
and rock, Evans et al predicted the failure mode using the

to the prediction of disaster in engineering. Keller observed the crack char-
acteristics in rock using a computed tomography technique
and investigated the damage properties of rock. All of the
above analyses showed that the study on the development of
crack and gas migration in coal is a hot spot for many
scholars. Moreover, the development of a gas-solid coupling
model in dual-porosity media and the application of numer-
ical methods are also the main directions for improving the
gas seepage theory in coal (rock).

The Datong mining area, which is an influential coal mine
region in China, is located in the northern Shanxi Province.
The Tashan coal mine, of which the extremely thick 3-5# coal
seam is a major minable seam, is the representative coal mine
of the Datong mining area. The roof of the 3-5# coal seam
consists of hard-and-thick strata, and abnormal gas emissions
occur from the process of coal mining, especially during roof
weighting. In this paper, the 8212 working face of the Tashan
coal mine in the Datong mining area was used as an exam-
ple, and the effect of the roof movement on gas flow in the
extremely thick coal seam under fully mechanized sublevel
caving (FMSC) mining conditions was studied. The purpose
was to address the problem of abnormal gas emission in the
FMSC faces of the extremely thick coal seams. Moreover, the
results can be used as a reference for other mining areas with
similar problems.

2 | STUDY AREA

2.1 | Geological background and the
coalbed storage feature

The Tashan coal mine locates on the middle-eastern Datong
coalfield, and the geographical position is 112°49′-113°9′
East longitude and 39°52′-40°10′ North latitude. The re-
coverable reserves and designed service life of the coal
mine are 3.07 × 10^7 t and 140 years, respectively. The gen-
eral stratigraphy of coal measures is exhibited in Figure
1. The coal seams in Tashan coal mine are 4#, 2#, 3-5#, and 8#, among which the 4# and 2# coal seams have no
mining value due to the destruction caused by the lampro-
phyre. There are eight panels in Tashan coal mine, and the
main mining seams of the 1# and 2# panels are the 3-5#
coal seam, of which the thickness is 15.72 m. The length of
the working faces is 220 m, and the mining method is the
FMSC mining for which the mining height and the caving
height are 3.5 and 12.5 m, respectively.
2.2 | Ventilation mode and gas parameters of coal seams

The ventilation mode of Tashan coal mine is the exhaust ventilation. The actual air supply amount of the 1# and 2# panels are $2 \times 10^4$ m$^3$/min and $1.4 \times 10^4$ m$^3$/min, respectively. The ventilation pattern of the working faces is the “U + I” type. The high drainage roadway locates in the rock strata of 3-5# coal seam upside, and the vertical distances from the coal seam roof are 20 m.

The gas pressure and contents of 3-5# coal seam are 0.12 MPa and 2.64 m$^3$/t, respectively. The gas permeability of the coal seam is $1.108 \times 10^{-4} - 1.328 \times 10^{-4}$ m$^2$/(MPa·d). Moreover, the hectometer borehole gas emission and the borehole gas attenuation coefficient of 3-5# coal seam are 0.0175-0.0192 m$^3$/min/hm and 0.572-0.743, respectively.

3 | EFFECT OF THE ROOF WEIGHTING ON GAS EMISSION IN WORKING FACES

The gas sources of the FMSC faces are the coal walls of the working faces and the fallen coals in goafs. For the slice mining of thick coal seams, the gas in the unmined layers may flow into the goaf. If there are several goafs in the study area, the gas in the other goafs may flow into the present goaf. Because of the impact of mining, stress, and ventilation conditions, the gas in the above area may flow continually into the working face.

3.1 | Gas emissions in working faces

To study the emission characteristics of gases in the FMSC faces of extremely thick coal seams in the study area, the 8212 working face of 2# panel in Tashan coal mine is used as a research object, and the variations of the gas concentration and emission rate at different locations are collected during the coal mining process, which is shown in Figures 2 and 3.

Figures 2 and 3 indicate that at the beginning of coal mining, the gas concentrations in the return airway and upper corner are small and exhibit no obvious changes during the coal mining process. However, the gas concentrations in the high drainage roadway, which first increases and then fluctuates continuously, are larger than those in the upper corner.
and return airway. Moreover, it is shown that the gas emission rate in high drainage roadway exhibits a same tendency with the total emission rate of gases, but the gas emission rate in the return airway is much smaller, which indicates that gases in coals are mainly extracted by the high drainage roadway and its design position is reasonable.

According to the field test and analysis on the emission characteristics of gases in 8212 working face, the gas emission laws in the working face of Tashan coal mine are mainly reflected as follows.

First, the absolute emission capacity of gases in mining coal seams is large. As mentioned above, the average thickness of 3-5# coal seam is 15.72 m, and the mining method is the FMSC mining. If its mining velocity is the same as conventional fully mechanized mining, the yield of 3-5# coal seam is 2-5 times larger than that of the coal seams using the conventional fully mechanized mining methods. Therefore, the absolute emission capacity of gases in 3-5# coal seam will increase exponentially when its gas content is the same as that of the other coal seams.

Second, the emission capacity of gases in the overlying adjacent coal seams is large. The FMSC mining method expands the range of influence on the upper coal seam and increases the height of the caving zone and fracture zone, which instigates gas emissions from the 2# and 4# coal seams.

Third, the emission capacity of gases in goafs is great. The recovery rate of coals in Tashan coal mine using the FMSC mining method is only 60%-80%, and many coals containing gas left in goafs, which results in the increased gas emission capacity in goafs. In addition, the roof of the 3-5# coal seam is the hard-thick lamprophyre, and the height of goafs is large; the roof collapse has a significant impact on the gas migration in goafs, and a great deal of gas may be squeezed into the working face.

According to the field observation data, the 8212 working face was connected to the high roadway on February 5, and then, the ventilation mode of the 8212 working face changed into the pattern of one intake airway and two return airways. The gas emission rate and the actual air supply amount of the 8212 working face are 18-23 and 3000-3800 m³/min, respectively. The gas concentration in the upper corner and return airway are 0.3% and 0.2%, respectively. However, after the drainage pump of the high drainage roadway was opened on March 24, the emission rate of gases in 8212 working face became 35-45 m³/min during the routine mining process. The actual air supply amount of 8212 working face, return
airway, and high drainage roadway are approximately 3000, 2200 and 780 m³/min, respectively, whereas the gas concentrations in the upper corner and return airway are only 0.15% and 0.1%-0.2%, respectively. Therefore, it is of great significance for safe mining to exhaust the gas by the high drainage roadway.

3.2 Effect of roof weighting on gas emission characteristics

Roof weighting is an important factor that results in the abnormal gas emissions of the working face during the coal mining process. During roof collapse, the vertical component of the impact forces can compact the residual coal and the rock refuse in the goaf; the horizontal component of the impact forces not only compacts the residual coal and the rock refuse but also strongly squeezes the gas in the goaf, which provides power for gas migration in the goaf.

The study on periodic roof weighting was mainly achieved by observing the resistance of the hydraulic supports. According to the statistics for the 8212 working face, the gas concentrations in the different locations and the gas emission rate of the 8212 working face with the resistance of hydraulic supports were obtained, as shown in Figures 4, 5, 6, and 7.

Figures 4, 5, 6, and 7 show that the concentration of gases in the upper corner, high drainage roadway, return airway, and the emission rate of gases corresponds well with the resistance of hydraulic supports during the coal mining process. After 8212 working face is in the stable period of coal mining, the gas concentration in the upper corner, high drainage roadway, and return airway are 0.2%, 3.8%, and 0.2%, respectively, and the emission rate of gases in 8212 working face is approximately 55 m³/min during the routine mining process. However, during roof weighting, the gas concentrations in the upper corner, high drainage roadway, and return airway increase suddenly to approximately 0.4%, 5.0%, and 0.5%, respectively, and the emission rate of gases increases sharply to approximately 70 m³/min.

The concentration and emission rate of gases in the high drainage roadway can characterize the gas emission law in goafs to a certain extent. To investigate the effect of roof weighting on gas emission in different stages, the gas concentrations and emission rates in the high drainage roadway and return airway of 8212 working face in the period of overhaul and production are shown in Table 1.

As shown in Table 1, the ventilation air methane (VAM) capacity in the return airway is 4.07 m³/min, and the methane drainage capacity in the high drainage roadway is 33.6 m³/min in the overhaul period. However, when roof weighting occurs in the overhaul period, the VAM capacity in the return airway is 6.33 m³/min, and the methane drainage capacity in the high drainage roadway is 46.8 m³/min.
During the production period, the VAM capacity in the return airway is 7.23 m\(^3\)/min, and the methane drainage capacity in the high drainage roadway is 49.2 m\(^3\)/min. However, when roof weighting occurs in the production period, the VAM capacity in the return airway is 9.72 m\(^3\)/min, and the methane drainage capacity in the high drainage roadway is 62.4 m\(^3\)/min. Therefore, in the overhaul period, the VAM capacity increases by 55.53\%, and the methane drainage capacity increases by 39.29\% when roof weighting occurs; in the production period, the VAM capacity increases by 34.44\%, and the methane drainage capacity increases by 26.83\% when roof weighting occurs. It is demonstrated that the disaster of gas exceeding the limit may easily occur during roof weighting.

4 | NUMERICAL ANALYSIS OF THE ROOF MOVEMENT ON GAS MIGRATION IN THE GOAF

After mining, damaged coals and rocks—residual coals, plus materials from the overlying strata and immediate roof—fill in goafs. Because of its high permeability and porosity, the caving zones contain gases, which may be from the adjacent unmined coal seams and/or the mined coal seams.\(^{38,41-43}\) The impact forces that are caused by the roof collapse have an important effect on the gas seepage field in goafs.

To study the gas migration in the goaf after the roof collapses, the following assumptions are made: (a) the gas flow in the coal mine roadways is the pipe flow; (b) the goaf is filled with porous media composed of coal and rock; (c) the system is isothermal; and (d) the coal and rock are saturated by gas, and the gas desorption is instantaneous.

4.1 | Governing equations

4.1.1 | Gas migration

The Navier-Stoke (N-S) equation can reveal the gas migration laws in a pipe for both the steady flow and turbulent flow.\(^{14}\) In this paper, the coal mine roadways are assumed to be the pipes; thus, the N-S equation, which is shown as follows, is considered to be the governing equation of gas migration:

\[
\begin{aligned}
- \nabla \cdot \eta \left( \nabla u_{ns} + (\nabla u_{ns})^T \right) + \rho u_{ns} \cdot \nabla u_{ns} + \nabla p &= 0 \\
\nabla \cdot u_{ns} &= 0
\end{aligned}
\]  \hspace{1cm} (1)

where \(\eta\) is the viscosity of fluids, kg/(m/s); \(u_{ns}\) is the velocity of fluids, m/s; \(\rho\) is the density of fluids, kg/m\(^3\); \(p\) is the pressure of fluids, Pa; and \(\nabla\) is the Hamiltonian operator.
**4.1.2 Porosity of the coal and rock**

Porous media consist of skeletons and pores; thus, the volume can be obtained as follows:

\[
\begin{align*}
V_1 &= V'_1 + V_0 \\
V_2 &= V'_2 + V'_0
\end{align*}
\]  

where \( V_1 \) and \( V_2 \) are the total volume of coal before and after deformation occurs, respectively, (given in m\(^3\)); \( V'_1 \) and \( V'_2 \) are the volumes of the coal pores before and after deformation occurs, respectively, (given in m\(^3\)); and \( V_0 \) and \( V'_0 \) are the coal skeleton volumes before and after deformation occurs, respectively, (given in m\(^3\)).

Based on the definition of porosity, we obtain the following:

\[
\begin{align*}
\phi_1 &= \frac{V'_1}{V_1} = \frac{V_1 - V_0}{V_1} \\
\phi_2 &= \frac{V'_2}{V_2} = \frac{V_2 - V'_0}{V_2}
\end{align*}
\]

4.1.3 Gas seepage

The gas flow in porous media meets Darcy's law\(^{26}\), thus, the gas seepage equation can be expressed as follows:

\[
\begin{align*}
v &= -\frac{k}{\mu} \nabla p \\
v_f &= -\frac{k_f d_f}{\mu} \nabla p
\end{align*}
\]

where \( v \) is the seepage velocity of gases in coals, m/s; \( v_f \) is the seepage velocity of gases in coal fractures, m/s; \( k \) is the permeability of coals, mD; \( k_f \) is the permeability of coal fractures, mD; \( \mu \) is the kinetic viscosity of gases, Pa/s; and \( d_f \) is the fracture width, m.

**TABLE 1** Gas concentration and emission rate in the high drainage roadway and return airway of 8212 working face in different stages

| Stage                        | Gas concentration/% | Actual air supply amount/(m\(^3\)/min) | Gas emission/(m\(^3\)/min) |
|------------------------------|---------------------|----------------------------------------|-----------------------------|
|                              | High drainage       | Return airway                          | High drainage               | Return airway               |                                |
| Overhaul period              | 2.8                 | 0.18                                   | 1200                        | 2260                        | 37.67                         |
| Overhaul period (roof        | 3.9                 | 0.28                                   | 1200                        | 2260                        | 53.13                         |
| weighting)                   |                     |                                        |                             |                             |                                |
| Production period            | 4.1                 | 0.32                                   | 1200                        | 2260                        | 56.43                         |
| Production period (roof       | 5.2                 | 0.43                                   | 1200                        | 2260                        | 72.12                         |

**FIGURE 8** Numerical model diagram of case 1

**Unit: m**
4.2 Numerical model of gas migration in the goaf

According to the field investigation, the collapse of the lower part of the lamprophyre in the roof can result in small roof weighting, and its roof weighting step is approximately 40 m; the collapse of the upper part of the lamprophyre in the roof can result in large roof weighting, and its roof weighting step is approximately 70 m. Based on the information, numerical models were developed.

Case 1: The load applied to the upper part of the goaf is 0.158 MPa after the roof collapses. The initial porosity of porous media in the goaf is 0.4. The height of the goaf is 11 m; however, near the working face, the roof is not completely broken and has a height of 22 m, which is shown in Figure 8.

Case 2: The load applied to the upper part of the goaf is 1.85 MPa after the roof collapses. The initial porosity of porous media in the goaf is 0.4. The height of the goaf is 19 m; near the working face, the height is 22 m, because the roof is not completely broken, which is shown in Figure 9.

The initial physical variable values of the numerical models are shown in Table 2.

5 RESULTS AND DISCUSSION

According to the above analysis, the impact forces that are caused by the roof collapse mainly change the flow state of the gas in the goaf, which determines the variation in the gas concentrations in the upper corner and return airway. Hence, it is quite significant to investigate the effect of impact forces caused by the roof collapse on the gas seepage field in goafs. Based on the assumptions and governing equations, the distribution of the gas concentration affected by roof collapse in the goaf can be obtained by numerical calculation.

Case 1: The effect of the collapse of the lower part of the lamprophyre on gas migration in the goaf is shown in Figures 10 and 11.

Case 2: The effect of the collapse of the upper part of the lamprophyre on gas migration in the goaf is shown in Figures 12 and 13.
Figures 10 and 12 reveal that at the moment of the roof collapse, the gas in the goaf flows into the return airway and high drainage roadway, which increases the gas concentration in the return airway, high drainage roadway, and upper corner. The gas concentration decreases gradually and tends to a normal state after reaching a maximum value. Figure 11 shows that at the moment of the lower part of the lamprophyre collapsing, the maximum gas concentrations in the return airway, upper corner, and high drainage roadway are 3.4%, 4.8%, and 5.6%, respectively. Figure 13 shows that at the moment of the upper part of the lamprophyre collapsing, the maximum gas concentrations in the return airways, upper corner, and high drainage roadway are 6.1%, 9.3%, and 8.3%, respectively. Thus, when the upper part of the lamprophyre collapses, the variation in the gas concentration in the upper corner is very pronounced, which easily results in a coal mine disaster. This is because the volume that is supported by the upper part of the lamprophyre is triple the size of that supported by the lower part of the lamprophyre, and the load that is caused by the upper part of the lamprophyre is much larger than that caused by the lower part of the lamprophyre. Therefore, the collapse of the upper part of the lamprophyre causes a greater disturbance than that of the lower part of the lamprophyre, which results in a larger gas emission capacity.
In fact, the upper corner and return airway have taken measures to prevent reaching the gas limit, which results in the unobvious variation in the gas concentrations in the return airway and upper corner. However, gas in the high drainage roadway is almost unaffected by human factors; thus, the gas concentration in the high drainage roadway can reflect the gas emission variations in goafs, as shown in Figure 5.

Figure 5 indicates that the gas concentration in the high drainage roadway agrees well with the resistance of hydraulic supports in the process of coal mining. The minor cycle of gas concentration changes is 6-7 days, which corresponds to 33.6-39.2 m of the roof weighting step; the major cycle of gas concentration changes is 11-13 days, which corresponds to 61.6-72.8 m of the roof weighting step. The largest gas concentrations in the minor cycle and in the major cycle are 6.1% and 7.9%, respectively, which is in accord with the results of the numerical simulation. This result indicates that it is effective to control the gas in coal seams by reasonably designing the location of the high drainage roadway in light of mining characteristics of coal seams and the gas emission law.

6 | CONCLUSION

In the paper, an extremely thick coal seam under FMSC mining conditions from Tashan coal mine in China was taken as an example; the gas emissions laws were studied, and the effect of roof movement on the gas flow in the goaf was analyzed. The following main conclusions can be drawn.
1. According to the analysis on the gas emission characteristics in Tashan coal mine, the mining coal seams, the overlying adjacent coal seams, and the goafs are the main contributors resulting in the large gas emission capacity of the FMSC working face during the coal mining process, and even situations exist where the gas concentration exceeds the limit in the working face.

2. The field test and analysis on the relationship between the concentration and emission rate of gases and the resistance of the hydraulic supports indicate that the roof weighting greatly increases the gas concentrations in the upper corner, high drainage roadway, and return airway and the gas emission rate during the coal mining process, which proves that the situation of gas concentration exceeding the limit may easily occur in the process of roof weighting.

3. A numerical simulation study on the gas emission law was carried out by taking the large roof weighting step and the small roof weighting step as the objects. The results are in good agreement with the change of observed data in the field, which indicates that it is effective to control the gas in coal seams by reasonably designing the location of the high drainage roadway according to the mining characteristics of the coal seams and the gas emission law.

ACKNOWLEDGMENTS

The authors are grateful to the financial support from the National Natural Science Foundation of China (51904310, 51874314, and 51774292), the Open Funds of State Key Laboratory Cultivation Base for Gas Geology and Gas Control (Henan Polytechnic University) (WS2018B06), and the Open Funds of Hebei State Key Laboratory of Mine Disaster Prevention (KJZH2017K02).

ORCID

Haijun Guo https://orcid.org/0000-0001-9022-3555

REFERENCES

1. Zhao K, Li Y. Analysis and development suggestion for coal resources safety in China. Coal Eng. 2018;50(10):185-189.
2. Wang L, Cheng Y, Liu H. An analysis of fatal gas accidents in Chinese coal mines. Safety Sci. 2014;62:107-113.
3. Kong H, Wang L. Seepage problems on fractured rock accompanying with mass loss during excavation in coal mines with karst collapse columns. Arab J Geosci. 2018;11:585.
4. Zhang C, Liu J, Zhao Y, Zhang L, Guo J. A fluid-solid coupling method for the simulation of gas transport in porous coal and rock media. Energy Sci Eng. 2019;7:1913-1924.
5. Zhang B, Li Y, Fantuzzi N, et al. Investigation of the flow properties of CBM based on stochastic fracture network modeling. Materials. 2019;12(15):2387.
6. Liu J, Zhang R, Song D, Wang Z. Experimental investigation on occurrence of gassy coal extrusion in coalmine. Safety Sci. 2019;113:362-371.
7. Lin J, Ren T, Cheng Y, Nemeck J, Wang G. Cyclic N2 injection for enhanced coal seam gas recovery: A laboratory study. Energy. 2019;188:116115.
8. Chen Z, Miao X, Liu W. Analysis on stability of parametric system of seepage flow in wall rock affected by mining. J Central South Univ Technol. 2004;35(1):129-132.
9. Palchik V. Formation of fractured zones in overburden due to longwall mining. Environ Geol. 2003;44(1):28-38.
10. Palchik V. Experimental investigation of apertures of mining-induced horizontal fractures. Int J Rock Mech Mining Sci. 2010;47(3):502-508.
11. Lu S, Cheng Y, Li W. Model development and analysis of the evolution of coal permeability under different boundary conditions. J Nat Gas Sci Eng. 2016;31:129-138.
12. Zhao YX, Gong S, Hao XJ, Peng Y, Jiang YD. Effects of loading rate and bedding on the dynamic fracture toughness of coal: laboratory experiments. Eng Fract Mech. 2017;178:375-391.
13. Yang TH, Xu T, Liu HY, Tang CA, Shi BM, Yu QX. Stress-damage-flow coupling model and its application to pressure relief coal bed methane in deep coal seam. Int J Coal Geol. 2011;86(4):357-366.
14. Wang L, Cheng L, Cheng Y, et al. Characteristics and evolutions of gas dynamic disaster under igneous intrusions and its control technologies. J Nat Gas Sci Eng. 2014;18:164-174.
15. Cheng Y, Zhang X, Wang L. Controlling effect of ground stress on gas pressure and outburst disaster. J Mining Safety Eng. 2013;30(3):408-414.
16. Lu SQ, Cheng YP, Li W, Wang L. Pore structure and its impact on CH4 adsorption capability and diffusion characteristics of normal and deformed coals from Qinzhou Basin. Int J Oil Gas Coal Technol. 2015;10(1):94-114.
17. Zhang Z, Cao S, Li Y, Guo P, Yang H, Yang T. Effect of moisture content on methane adsorption- and desorption-induced deformation of tectonically deformed coal. Adsorp Sci Technol. 2018;36(9–10):1648-1668.
18. Gray I. Reservoir engineering in coal seams: Part I-The physical process of gas storage and movement in coal seams. SPE Reservoir Eng. 1987;2(1):28-34.
19. Li W, Cheng Y, Guo P, An F, Chen M. The evolution of permeability and gas composition during remote protective longwall mining and stress-relief gas drainage: a case study of the underground Haishiwan Coal Mine. Geosci J. 2014;18(4):427-437.
20. Wang L, Cheng Y-P, Li F-R, Wang H-F, Liu H-B. Fracture evolution and pressure relief gas drainage from distant protected coal seams under an extremely thick key stratum. J China Univ Mining Technol. 2008;18(2):182-186.
21. Guo W, Wang H, Chen S. Coal pillar safety and surface deformation characteristics of wide strip pillar mining in deep mine. Arab J Geosci. 2016;9(2):1-9.
22. Zhao Y, Cao S, Li Y, et al. The occurrence state of moisture in coal and its influence model on pore seepage. RSC Adv. 2018;8(10):5420-5432.
23. Zhou S, Sun J. The theory of gas flow in coal seams and its application. J China Coal Soc. 1965;2(1):24-37.
24. Qian M, Xu J. Study on the “O-shape” circle distribution characteristics of mining induced fractures in the overlaying strata. J China Coal Soc. 1998;23(5):466-469.
25. Xie HP, Zhou HW, Liu JF, et al. Mining-induced mechanical behavior in coal seams under different mining layouts. J China Coal Soc. 2011;36(7):1067-1074.
26. Zhou S, He X. Rheological hypothesis of coal and methane outburst mechanism. J China Univ Mining Technol. 1990;19(2):1-8.
27. Xue D, Zhou H, Wang C, Gao H. Percollation model of mining-induced crack evolution of the overlying strata. J China Univ Mining Technol. 2013;42(06):917-922.
28. Xu J, Zhang P, Li N. Deformation properties of rock mass with intermittent cracks under cyclic loading. Chin J Geotech Eng. 2008;30(6):802-806.
29. Evans AG, Linzer M. Failure prediction in structural ceramics using acoustic emission. J Am Ceramic Soc. 1973;56(11):575-581.
30. Yamada I, Masuda K, Mizutani H. Electromagnetic and acoustic emission associated with rock fracture. Phys Earth Planet Inter. 1989;57(1):157-168.
31. Lockner D. The role of acoustic emission in the study of rock fracture. Int J Rock Mech Mining Sci Geomech Abs. 1993;30(7):883-899.
32. Yin F. A basic study for predicting the disaster in rock engineering with an acoustic emission technique. Eng Fract Mech. 1993;45(3):387-391.
33. Antonellini MA, Aydin A, Pollard DD. Microstructure of deformation bands in porous sandstones at Arches National Park, Utah. J Struct Geol. 1994;16(7):941-959.
34. Keller A. High resolution, non-destructive measurement and characterization of fracture apertures. Int J Rock Mech Mining Sci. 1998;35(8):1037-1050.
35. Schatzel SJ, Krog RB, Dougherty H. Methane emissions and airflow patterns on a longwall face: Potential influences from longwall gob permeability distributions on a bleederless longwall. Trans Soc Min Metall Explor Inc. 2017, 342, 51-61.
36. Cheng Y, Wang L, Zhang X. Environmental impact of coal mine methane emissions and responding strategies in China. Int J Greenh Gas Con. 2011;5(1):157-166.
37. Zhang L, Zhang C, Tu S, Tu H, Wang C. A Study of directional permeability and gas injection to flush coal seam gas testing apparatus and method. Transp Porous Media. 2016;111(3):573-589.
38. Zhang C, Tu S, Zhao Y. Compaction characteristics of the caving zone in a longwall goaf: a review. Environ Earth Sc. 2019;78:27.
39. Zhang R, Cheng YP, Zhou HX, et al. New insights into the permeability-increasing area of overlying coal seams disturbed by the mining of coal. J Nat Gas Sci Eng. 2018;49:352-364.
40. Yu Q, Cheng Y. Coal Mine Gas Control. Xuzhou: China University of Mining and Technology Press; 2012.
41. Wang K, Jiang SG, Wu ZY, et al. Intelligent safety adjustment of branch airflow volume during ventilation-on-demand changes in coal mines. Process Safety Environ Protect. 2017;111:491-506.
42. Li Z, Feng G, Jiang H, et al. The correlation between crushed coal porosity and permeability under various methane pressure gradients: a case study using Jincheng anthracite. Greenh Gas Sci Technol. 2018;8:493-509.
43. Lu S, Zhang Y, Sa Z, Si S, Shu L, Wang L. Damage-induced permeability model of coal and its application to gas predrainage in combination of soft coal and hard coal. Energy Sci Eng. 2019;7:1352-1367.
44. Munson BR, Okiishi TH, Huebsch WW, Rothmayer AP. Fluid Mechanics. Singapore: Wiley; 2013.

How to cite this article: Guo H, Li X, Cui H, Chen K, Zhang Y. Effect of roof movement on gas flow in an extremely thick coal seam under fully mechanized sublevel caving mining conditions. Energy Sci Eng. 2020;8:677–688. https://doi.org/10.1002/ese3.541