Research Article

Evolution Law of Gas Discharge of Carbon Monoxide in Mining Extra-Thick Coal Seam of Datong Mining Area

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In order to reveal the evolution law of gas discharge of carbon monoxide in mining an extra-thick coal seam of the Datong mining area by the numerical simulation and field monitoring test, the 8202 working face and 8309 working face in the Tongxin coal mine are chosen as the test sites. The results show that the seepage flow of carbon monoxide gas reaches $1.854 \times 10^{-8} \text{ m}^3/\text{s}$ in the #1 fracture after the #3 key stratum in the far field breaks in the 8202 working face, the seepage flow of carbon monoxide gas reaches $1.307 \times 10^{-7} \text{ m}^3/\text{s}$ in the #2 fracture, the seepage flow of carbon monoxide gas reaches $4.276 \times 10^{-7} \text{ m}^3/\text{s}$ in the #3 fracture, the seepage flow of carbon monoxide gas reaches $4.192 \times 10^{-7} \text{ m}^3/\text{s}$ in the #4 fracture, and the seepage flow of carbon monoxide gas reaches $1.623 \times 10^{-7} \text{ m}^3/\text{s}$ in the #5 fracture. The initial caving of the #3 key stratum in the far field occurs and collapses to the gob, when the working face in the #3-5 coal seam advances to 180 m, and the voussoir beam forms in the #3 key stratum. Besides, a shower shape was formed by the seepage flow of carbon monoxide gas, and the maximum flow in the working face reaches $4.562 \times 10^{-4} \text{ m}^3/\text{s}$. When the 8309 working face advances from 521.2 m to 556.4 m, the air pressure at the working face gradually rises and reaches the maximum magnitude and then begins to decrease; when the working face advances to 556.4 m, the air pressure at the working face reaches the maximum magnitude of 91.35 kPa. The gas discharge disaster of carbon monoxide in mining the extra-thick coal seam of the Datong mining area is effectively controlled by the dynamic balance multipoint control technology. The research results can be treated as an important theoretical basis for the prevention and treatment for carbon monoxide discharge disaster in mining the extra-thick coal seam of the Datong mining area.

1. Introduction

Coal resource is the one of the kinds of basic energy for economy and social development, and the sustainable development of the coal industry is closely related to economic and social development and energy security in China [1]. Besides, CO (carbon monoxide) is widely recognized as the most important symbol gas for detecting coal spontaneous combustion at the early stage [2]. However, CO overrunning occurs in a large number of field practices in coal mines, especially in mining the thick coal seam [3, 4]. Meanwhile, CO is a toxic and harmful gas, which poses a serious threat to the safety and health of miners [5]. The concentration of CO in the working face cannot exceed 0.0024%, which is

the requirement of “the safety regulation for coal mining” in China [6, 7]. For example, the carbon monoxide gas discharge disaster occurred in the Tongxin coal mine in Shanxi province, which greatly affected the safety mining production [8, 9]. Therefore, it is of great significance to research the evolution law of gas discharge of carbon monoxide in mining an extra-thick coal seam, in order to guarantee the safe mining in the Datong mining area.

The scholars at home and abroad have carried out lots of research on the evolution law of gas discharge of carbon monoxide in mining a coal seam. Zhai et al. [10] analyzed the CO gas sources and influence factors in the working face and established a quantitative calculation model of the CO gas content, based on the CO gas produced mechanism from

the coal oxidization process. Jia et al. [11] put forward the viewpoint that the source of carbon monoxide was comprised of the primal and secondary carbon monoxide by means of theoretical analysis combining with coal mine fire prevention theory, coal geology theory, gas geology theory, and coal chemistry theory. Yu et al. [12] analyzed the roof collapse of a crack zone in a carboniferous coal seam and the stress influence law of a coal pillar in a mined-out area of the Jurassic coal seam and obtained the mechanism of strong pressure revealed under the influence of a mining dual system of the coal pillar. Chen et al. [13] analyzed the overburden movement and failure law caused by double period coal seam mining by using the key strata theory, physical detection, and numeric simulation technology. Tang et al. [14] investigated the microseismic events of space-time evolution characteristics under the influence of a complex mined-out area at the upper Jurassic coal seam group and obtained the relationship of strata movement and rock pressure under the influence of double series coal seams. Meng [15] determined the cracking connection in the overburden strata above the double system seam mining in the Datong mining area, according to the discharging disaster of accumulated water and harmful gas in the gob, caused by the developed and connected cracks in the overburden strata above each seam after the mining of the multi-seams. Zhang et al. [16] established a dynamic load calculation method for the unextracted area, coal pillar area, and mining collapse area of the upper coal seams and studied the dynamic deformation of overlying strata and pressure behavior, according to the mining condition of multiple coal seams with deep overburden strata and a large panel in the Datong mining area. Yu et al. [17] analyzed the impact process of a hard roof breaking to the gob and got the relationship between the axial force of the broken block and the broken expansion coefficient of caving coal-rock in the gob, in order to deal with the issue of the abnormal gas emission during periodic weighting, based on the "O-X"-type breaking of the hard roof.

At present, many scholars at home and abroad have studied the evolution law of gas discharge of carbon monoxide in mining a coal seam, whose thickness is less than 8 m [18–20]. The average mining thickness of the #3-5 coal seam in the Datong mining area is 15 m; therefore, the working face is easily connected with the above abandoned gob, where CO gas is accumulated by the mining-induced fractures in the overburden, leading to the gas discharge disaster of carbon monoxide. However, the evolution law of gas discharge of carbon monoxide in mining the extra-thick coal seam of the Datong mining area is not researched systematically and deeply [21–23]. Based on the mining and geological conditions of the 8202 working face and the 8309 working face in the Tongxin coal mine in Shanxi province, the evolution law of the gas discharge of carbon monoxide in mining the extra-thick coal seam of the Datong mining area is studied, by the numerical simulation and field monitoring test. The research results can be treated as an important basis for the prevention and treatment of carbon monoxide discharge disaster in mining extra-thick coal seams.

2. Numerical Calculation Simulation of Gas Discharge of Carbon Monoxide

2.1. Numerical Calculation Model. The numerical calculation model of the CO gas discharge is established in UDEC software, which is shown in Figure 1. The extra-thick coal seam is the coal seam whose thickness is larger than 8 m. There are three key strata in the overburden of the 8202 working face, namely, the #1 key stratum (lower part in the near field), #2 key stratum (upper part in the near field), and #3 key stratum (whole part in the near field). The key stratum refers to the stratum which controls the whole or partial overburden movement from the overburden to the surface. Besides, the thickness of the #14 coal seam is 4 m, the thickness of the #3-5 coal seam is 15 m, and the distance between the #14 coal seam and the #3-5 coal seam is 160 m.

In the numerical calculation simulation, the #14 coal seam is mined, followed by the #3-5 coal seam, and the mining step is 15 m. The gas pressure in the gob in the #14 coal seam is set to 0.1 MPa, and the gas pressure in the gob in the #3-5 coal seam is set as negative. The physical parameters of the rock mass are obtained by the rock mechanics experiments, as shown in Table 1.

2.2. Numerical Calculation Results. The initial caving of the direct roof occurs, when the 8202 working face in the #3-5 coal seam advances to 45 m, and the transverse fractures on the top rapidly develop to the bottom of the #1 key stratum in the near field. The pore pressure at the top of the #3 key stratum in the far field reaches the maximum of 0.1 MPa, and the pressure is not transferred to the bottom of the #3 key stratum in the far field, as shown in Figure 2.

The harmful gas in the gob comes from the left coal spontaneous combustion [24, 25]. And the discharge of harmful gas is controlled by negative pressure ventilation. From the perspective of flow distribution, the CO gas flow rate at both ends of the floor of the coal seam reaches the maximum magnitude $0.0293 \text{ m}^3/\text{s}$, since both ends of the gob of the #14 coal seam have the largest fracture development depth and fracture opening degree, located within 1 m below the floor at both ends. Besides, the flow rate outside 1 m below the floor of the coal seam rapidly drops to $1.362 \times 10^{-7} \text{ m}^3/\text{s}$, which varies greatly in magnitude. Meanwhile, it is obvious that the seepage phenomenon occurs in some primary joints prefabricated in the #3 key stratum in the far field, and the seepage flow is $1.634 \times 10^{-7} \text{ m/s}$, with the extremely low seepage flow. In addition, the maximum seepage flow of the roof of the #3-5 coal seam is $3.285 \times 10^{-8} \text{ m/s}$, located at 7 m in the direct roof, which is mainly derived from the extremely low seepage flow generated by partial primary fractures, as shown in Figure 3.

The initial caving of the #1 key stratum in the near field occurs and collapses to the gob, when the working face in the #3-5 coal seam advances to 105 m. The distance between the #1 key stratum and the #2 key stratum in the near field is only 6 m. The overburden deformation and movement caused by the break of the #1 key stratum have a significant impact on the #2 key stratum, resulting in obvious longitudinal and transverse fractures in the #2 key stratum. The

FIGURE 1: The numerical calculation model of gas discharge of carbon monoxide.

TABLE 1: The physical parameters of rock mass.

Rock strata	K (GPa)	G (GPa)	d (N·m ⁻³)	f (°)	C (MPa)	t (MPa)
Coarse sandstone	10.85	7.5	2540	35	12.5	2.56
Sandy mudstone	30.35	14.74	2693	35	12.5	4.4
Medium sandstone	23.24	15.93	2654	35	12.5	5.72
Fine sandstone	19.79	19.86	2700	34	4.8	6.4
Siltstone	18.50	16.02	2604	34	4.8	4.89
Coal seam	3.89	1.59	1426	42	2.01	1.6

FIGURE 2: The pore pressure distribution in initial caving of direct roof.

maximum pore pressure above the key stratum in the far field is 0.1 MPa, as shown in Figure 4.

From the perspective of flow distribution, the fractures in overburden above the #1 key stratum in the near field further develop, especially the primary fractures of the key stratum in the far field; therefore, the CO gas penetrates down through primary fractures in the #3 key stratum with a small flow rate and enters the key seepage passage in the working face. The

seepage flow of the #3 key stratum in the far field increases to $2.250 \times 10^{-7} \text{ m}^3/\text{s}$, and the maximum flow in the working face reaches $1.655 \times 10^{-4} \text{ m}^3/\text{s}$, which increases by nearly ten thousand times, as shown in Figure 5.

The initial caving of the #2 key stratum in the near field occurs and collapses to the gob, when the working face in the #3-5 coal seam advances to 120 m. Tensile fractures occur in the lower part of the #3 key stratum in the far field and the

FIGURE 3: The flow distribution in initial caving of direct roof.

FIGURE 4: The pore pressure distribution in initial caving of #1 key stratum.

FIGURE 5: The flow distribution in initial caving of #1 key stratum.

upper part of the #3 key stratum above the central position of the gob. However, the development of fractures above the #3 key stratum is low, because the #3 key stratum is unbroken,

whose deformation and movement is small. Meanwhile, the maximum pore pressure at the top of the #3 key stratum is almost constant, as shown in Figure 6.

FIGURE 6: The pore pressure distribution in initial caving of #2 key stratum.

FIGURE 7: The flow distribution in initial caving of #2 key stratum.

FIGURE 8: The pore pressure distribution in initial caving of #3 key stratum.

From the perspective of the flow distribution, the fracture opening of the #3 key stratum in the far field continues to increase, after the break of the #2 key stratum in the near field. Specifically, the seepage flow of the CO gas reaches

$1.393 \times 10^{-8} \text{ m}^3/\text{s}$ in the #1 fracture, the seepage flow of the CO gas reaches $6.143 \times 10^{-8} \text{ m}^3/\text{s}$ in the #2 fracture, the seepage flow of the CO gas reaches $3.736 \times 10^{-7} \text{ m}^3/\text{s}$ in the #3 fracture, the seepage flow of the CO gas reaches $2.329 \times$

FIGURE 9: The flow distribution in initial caving of #3 key stratum.

(a) Empty box barometer

(b) Medium speed air gauge

(c) Dry and wet thermometer

(d) Ventilation multiparameter tester

FIGURE 10: Air pressure observation instruments.

TABLE 2: Comprehensive table of air pressure observations at the working face.

Number of times	Measurement points	1	2	3	4	5	6	7	8
1	Barometric pressure reading (mmHg)	679.8	679.6	679.5	679.1	678.5	678.0	678.5	678.5
	Pressure (kPa)	90.34	90.32	90.30	90.25	90.17	90.10	90.17	90.17
2	Barometric pressure reading (mmHg)	680.6	680.1	680.5	680.0	680.3	679.8	680.0	679.9
	Pressure (kPa)	90.45	90.38	90.43	90.37	90.40	90.34	90.37	90.36
3	Barometric pressure reading (mmHg)	683.4	683.3	683.2	682.9	682.6	683.1	682.6	682.2
	Pressure (kPa)	90.82	90.81	90.79	90.75	90.71	90.78	90.71	90.66
4	Barometric pressure reading (mmHg)	683.0	683.2	683.0	682.6	682.9	683.0	683.1	683.5
	Pressure (kPa)	90.77	90.79	90.77	90.71	90.75	90.77	90.78	90.83
5	Barometric pressure reading (mmHg)	683.7	683.4	683.1	682.9	682.9	682.9	683.0	683.5
	Pressure (kPa)	90.86	90.82	90.78	90.75	90.75	90.75	90.77	90.83
6	Barometric pressure reading (mmHg)	687.5	687.3	687.0	687.2	687.2	687.5	687.4	687.4
	Pressure (kPa)	91.37	91.34	91.30	91.33	91.33	91.37	91.35	91.35
7	Barometric pressure reading (mmHg)	687.8	687.8	687.6	687.8	687.0	686.2	686.5	687.2
	Pressure (kPa)	91.41	91.41	91.38	91.41	91.30	91.19	91.23	91.33
8	Barometric pressure reading (mmHg)	683.8	683.6	683.0	683.0	683.3	683.8	683.5	683.2
	Pressure (kPa)	90.87	90.85	90.77	90.77	90.81	90.87	90.83	90.79
9	Barometric pressure reading (mmHg)	684.5	684.6	684.6	684.5	684.6	684.7	684.9	684.6
	Pressure (kPa)	90.97	90.98	90.98	90.97	90.98	90.99	91.02	90.98
10	Barometric pressure reading (mmHg)	683.2	683	683.4	683.1	683.4	683.2	683.6	683.5
	Pressure (kPa)	90.79	90.77	90.82	90.78	90.82	90.79	90.85	90.83

10^{-7} m³/s in the #4 fracture, and the seepage flow of the CO gas reaches 1.128×10^{-7} m³/s in the #5 fracture. Besides, a shower shape is formed by the seepage flow of the CO gas, and the maximum flow in the working face reaches 8.285×10^{-4} m³/s, as shown in Figure 7.

The initial caving of the #3 key stratum in the far field occurs and collapses to the gob, when the working face in the #3-5 coal seam advances to 180 m, and the voussoir beam forms in the #3 key stratum. The upper strata of the #3 key stratum in the far field are in the state of compression, and the strata dislocation appear in the tensile fractures, located in the two solid ends of the strata. With the continuous advance of the panel, the overburden strata fracture periodically, and a fracture surface with a certain angle is formed in the coal seam, which is called the fracture surface. Besides, the formed tensile fractures are the key seepage passage for the CO gas, which flows into the fractures in the #3 key stratum in the far field and enters the working face, through the fracture surface in the underlying overburden. The maximum pore pressure at the top of the #3 key stratum in the far field is almost constant, as shown in Figure 8.

From the perspective of the flow distribution, when the break of the #3 key stratum in the far field occurs, the seepage flow of the CO gas reaches 1.854×10^{-8} m³/s in the #1 fracture, the seepage flow of the CO gas reaches 1.307×10^{-7} m³/s in the #2 fracture, the seepage flow of the CO gas reaches 4.276×10^{-7} m³/s in the #3 fracture, the seepage flow of the CO gas reaches 4.192×10^{-7} m³/s in the #4 fracture, and the seepage flow of the CO gas reaches 1.623×10^{-7} m³/s in the #5 fracture. Besides, a shower shape is

formed by the seepage flow of the CO gas, and the maximum flow in the working face reaches 4.562×10^{-4} m³/s, as shown in Figure 9.

3. Field Monitoring Test of Gas Discharge of Carbon Monoxide

3.1. Field Monitoring for Air Pressure. The Carboniferous #3-5 coal seam is mined at the working face in the Tongxin coal mine, and the fully mechanized caving mining technology is adopted. In order to verify whether the gas in the mined-out area has leaked, field monitoring for air pressure is carried out in the 8309 working face. Eight air pressure observation points are designed and arranged in the working face. The instruments used for barometric observation include empty box barometers, medium-speed wind meters, dry and wet thermometers, and ventilation multiparameter detectors, as shown in Figure 10.

The observation time of each measuring point is 15 minutes, and the field observation is made at the same time every day, ensuring that the observation interval is 24 hours, and the total observation period is 10 days. The observation results are shown in Table 2.

During the observation period, the air pressure of observation points is basically similar; therefore, the data of the #4 measuring point and the #5 measuring point are selected. When the working face advances from 521.2 m to 556.4 m, the air pressure in the working face gradually rises and reaches the maximum value and then begins to decrease; when the working face advances to 556.4 m, the air pressure at the working face reaches the maximum value of 91.35 kPa.

When the working face advances from 521.2 m to 546.8 m, the difference of the air pressure between the working face and the ground surface gradually decreases, the difference of the air pressure gradually increases from 546.8 m to 556.4 m, and the difference of the air pressure decreases from 556.4 m to 570.8 m.

3.2. Dynamic Balance Multipoint Control Technology. The negative pressure ventilation is adopted in the working face, which induces the CO gas from the overlying gob to leak to the working face, resulting in the CO gas concentration and harmful gas being overrun in the working face. Therefore, the dynamic balance multipoint control technology is put forward to deal with the practice problem. Three pressure-equalizing regulating valves are constructed in the intake airway. The first regulating valve is about 30 m away from the roadway entrance, and three local fans are installed in the intake airway in turn. Each fan has two stages, and the suction air volume is about 1000 m³/min, the three fans are started at the same time, and the supply air volume reaches 2300 m³/min. By gradually adjusting the intake airway and return airway to adjust the pressure difference and air volume inside and outside the damper, the purpose of CO emission control is effectively achieved.

4. Conclusions

- (1) The initial caving of the #2 key stratum in the near field occurs when the 8202 working face in the #3-5 coal seam advances to 120 m. The seepage flow of the CO gas reaches 1.393×10^{-8} m³/s in the #1 fracture in overburden, the seepage flow of the CO gas reaches 6.143×10^{-8} m³/s in the #2 fracture, the seepage flow of the CO gas reaches 3.736×10^{-7} m³/s in the #3 fracture, the seepage flow of the CO gas reaches 2.329×10^{-7} m³/s in the #4 fracture, and the seepage flow of the CO gas reaches 1.128×10^{-7} m³/s in the #5 fracture. Besides, the maximum flow in the 8202 working face reaches 8.285×10^{-4} m³/s
- (2) The initial caving of the #3 key stratum in the far field occurs when the working face advances to 180 m. The seepage flow of the CO gas reaches 1.854×10^{-8} m³/s in the #1 fracture, the seepage flow of the CO gas reaches 1.307×10^{-7} m³/s in the #2 fracture, the seepage flow of the CO gas reaches 4.276×10^{-7} m³/s in the #3 fracture, the seepage flow of the CO gas reaches 4.192×10^{-7} m³/s in the #4 fracture, and the seepage flow of the CO gas reaches 1.623×10^{-7} m³/s in the #5 fracture. Besides, a shower shape is formed by the seepage flow of the CO gas, and the maximum flow in the working face reaches 4.562×10^{-4} m³/s
- (3) When the working face advances from 521.2 m to 556.4 m, the air pressure at the working face gradually rises and reaches the maximum value and then begins to decrease; when the working face advances to 556.4 m, the air pressure at the working face reaches the maximum value of 91.35 kPa. The differ-

ence of the air pressure gradually increases from 546.8 m to 556.4 m and decreases from 556.4 m to 570.8 m. Besides, the gas discharge disaster of carbon monoxide in mining an extra-thick coal seam is effectively controlled by the dynamic balance multipoint control technology

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] H. X. Lin, F. Yang, Z. Z. Cao, Y. Wang, and X. J. Jiao, "Disastrous mechanism of water discharge in abandoned gob above the stope in mining extra-thick coal seam," *Geofluids*, vol. 2021, Article ID 6633517, 10 pages, 2021.
- [2] J. Li, "Validation methods of upper long distance goaf harmful gas discharge based on drilling camera and tracer technology," *Safety in Coal Mines*, vol. 50, no. 8, pp. 80–83, 2019.
- [3] B. Yu, W. B. Zhu, R. Gao, and J. R. Liu, "Strata structure and its effect mechanism of large space stope for fully-mechanized sublevel caving mining of extremely thick coal seam," *Journal of China Coal Society*, vol. 41, no. 3, pp. 571–580, 2016.
- [4] Z. Z. Cao, Y. L. Ren, Q. T. Wang, B. H. Yao, and X. C. Zhang, "Evolution mechanism of water-conducting channel of collapse column in karst mining area of Southwest China," *Geofluids*, vol. 2021, Article ID 6630462, 8 pages, 2021.
- [5] D. P. Zhang, Z. G. Wang, Y. Sun, and M. L. Zhou, "Research status and trend of CO overrunning in coal mines of China," *Safety in Coal Mines*, vol. 44, no. 4, pp. 183–185, 2013.
- [6] Y. Xue, T. Teng, F. Dang, Z. Ma, S. Wang, and H. Xue, "Productivity analysis of fractured wells in reservoir of hydrogen and carbon based on dual-porosity medium model," *International Journal of Hydrogen Energy*, vol. 45, no. 39, pp. 20240–20249, 2020.
- [7] H. Wen, J. Guo, Y. F. Jin, Z. F. Zhao, and Z. J. Yu, "Research status and trend of CO generation mechanism and control technology in coal mines," *Safety in Coal Mines*, vol. 46, no. 6, pp. 175–177, 2015.
- [8] J. C. Li, "Analysis and prevention of CO overrun in full-mechanized caving mining face," *Coal Mining Technology*, vol. 17, no. 5, pp. 91–94, 2012.
- [9] Y. Xue, F. Gao, Y. N. Gao, X. Liang, Z. Z. Zhang, and Y. Xing, "Thermo-hydro-mechanical coupled mathematical model for controlling the pre-mining coal seam gas extraction with slotted boreholes," *International Journal of Mining Science and Technology*, vol. 27, no. 3, pp. 473–479, 2017.

- [10] X. W. Zhai, L. J. Ma, and J. Deng, "Study and application of CO content prediction model to upper corner of coal mining face," *Coal Science and Technology*, vol. 39, no. 11, pp. 59–62, 2011.
- [11] H. L. Jia, M. G. Yu, and Y. L. Xu, "Analysis on the genetic type and mechanism identification of carbon monoxide in the coal-mine," *Journal of China Coal Society*, vol. 38, no. 10, pp. 1812–1818, 2013.
- [12] B. Yu, C. Y. Liu, J. X. Yang, and J. R. Liu, "Mechanism of strong pressure reveal under the influence of mining dual system of coal pillar in Datong mining area," *Journal of China Coal Society*, vol. 39, no. 1, pp. 40–46, 2014.
- [13] Y. Chen, H. W. Zhang, Z. H. Zhu, B. Yu, and L. J. Huo, "Research on the law overburden movement and failure under the influence of double period coal seam mining," *The Chinese Journal of Geological Hazard and Control*, vol. 25, no. 3, pp. 67–73, 2014.
- [14] G. S. Tang, Z. H. Zhu, Y. L. Han, and Z. Li, "Relationship between overburden strata movement and strata behavior during dual system seam mining based on microseismic monitoring technology," *Journal of China Coal Society*, vol. 42, no. 1, pp. 212–218, 2017.
- [15] X. B. Meng, "Safety and high efficient mining technology of ultra thick seam with double system interaction in Datong mining area," *Coal Science and Technology*, vol. 45, no. 8, pp. 114–120, 2017.
- [16] X. Zhang, C. B. Deng, and X. F. Wang, "Study on dynamic deformation of overlying strata and pressure behavior law for extraction of multiple coal seams," *Coal Science and Technology*, vol. 45, no. 9, pp. 103–108, 2017.
- [17] B. Yu, B. W. Xia, and P. Yu, "Effect of hard roof breaking on gas emission in fully-mechanized sublevel caving mining of extremely thick coal seam," *Journal of China Coal Society*, vol. 43, no. 8, pp. 2243–2249, 2018.
- [18] Y. Xue, P. G. Ranjith, F. Dang et al., "Analysis of deformation, permeability and energy evolution characteristics of coal mass around borehole after excavation," *Natural Resources Research*, vol. 29, no. 5, pp. 3159–3177, 2020.
- [19] Z. Z. Cao, P. Xu, Z. H. Li, M. X. Zhang, Y. Zhao, and W. L. Shen, "Joint bearing mechanism of coal pillar and backfilling body in roadway backfilling mining technology," *CMC-Computers Materials & Continua*, vol. 54, no. 2, pp. 137–159, 2018.
- [20] W. L. Shen, J. B. Bai, W. F. Li, and X. Y. Wang, "Prediction of relative displacement for entry roof with weak plane under the effect of mining abutment stress," *Tunnelling and Underground Space Technology*, vol. 71, pp. 309–317, 2018.
- [21] Y. Xue, J. Liu, F. Dang, X. Liang, S. Wang, and Z. Ma, "Influence of CH₄ adsorption diffusion and CH₄-water two-phase flow on sealing efficiency of caprock in underground energy storage," *Sustainable Energy Technologies and Assessments*, vol. 42, article 100874, 2020.
- [22] B. H. Yao, Z. W. Chen, J. P. Wei, T. H. Bai, and S. M. Liu, "Predicting erosion-induced water inrush of karst collapse pillars using inverse velocity theory," *Geofluids*, vol. 2018, Article ID 2090584, 18 pages, 2018.
- [23] Y. Xue, J. Liu, P. G. Ranjith, X. Liang, and S. Wang, "Investigation of the influence of gas fracturing on fracturing characteristics of coal mass and gas extraction efficiency based on a multi-physical field model," *Journal of Petroleum Science and Engineering*, vol. 206, article 109018, 2021.
- [24] Z. Z. Cao, F. Du, Z. H. Li, Q. T. Wang, P. Xu, and H. X. Lin, "Research on instability mechanism and type of ore pillar based on the fold catastrophe theory," *CMES-Computer Modeling in Engineering & Science*, vol. 113, no. 3, pp. 287–306, 2017.
- [25] L. Zhu, F. Dang, Y. Xue, K. Jiao, and W. Ding, "Multivariate analysis of effects of microencapsulated phase change materials on mechanical behaviors in light-weight aggregate concrete," *Journal of Building Engineering*, vol. 42, article 102783, 2021.