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Numerical Simulation Study on the Influencing Factors and Laws of Gas Emission in Coal Mine Excavation Face

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Abstract: In order to clarify the influencing factors and variation rules of gas emission in the excavation face, the 4301-working face of the East Well of Sihe Mine was taken as the research object. Through laboratory experiments, the influence characteristics of coal structure and gas content on gas emission rate were analyzed. Furthermore, the COMSOL Multiphysics numerical simulation software was used to investigate the influence of gas pressure, excavation speed, and soft layer thickness on the gas emission rate of the excavation face. The research results show that the gas emission rate is not only affected by the coal structure and gas content, but also by gas pressure, excavation speed, and soft layer thickness. The amount of gas emission is positively correlated with gas pressure, and the higher the gas pressure, the greater the amount of gas emission. The gas emission rate increases linearly with the excavation speed, and the influence of soft layer thickness on the gas emission rate increases with the increase of excavation speed.

Keywords: Coal Mine; Excavation Working Face; Gas Emission Rate; COMSOL Multiphysics Software; Influence Factor.

1. Introduction

Coal mine gas outburst is one of the main factors threatening coal mine safety production [1,2]. With the extension of mining level, the amount of gas emission gradually increases, making gas management and control more difficult, seriously affecting safety production [3-5]. The amount of coal mine gas emission is controlled by various factors, and many scholars in China have conducted extensive research on the influencing factors and laws of coal mine gas emission. Lv Fu et al. [6] used principal component analysis to determine the factors that affect the gas emission rate of the mining face, including interlayer spacing, interlayer lithology, and mining depth. Fu Hua et al. [7] established a coal mine gas emission prediction model based on coupling algorithm, and studied the influence of factors such as coal seam burial depth, coal seam thickness, and working face length on the absolute gas emission of coal mines. Liu Xiaohu et al. [8] obtained the law that the amount of gas emission increases with the increase of mining pressure in the working face based on monitoring data such as on-site support resistance, advanced support pressure, and gas concentration in the working face. Ye Chuan et al. [9] studied the gas emission rate in high gas excavation working faces and analyzed the correlation between gas emission rate in excavation tunnels and factors such as coal particle size and tunnel length. Gao Liang et al. [10,11] studied the main controlling factors affecting gas emission based on the mining face of the Buertai mine, and proposed that the factors affecting gas emission mainly include coal seam gas content, mining depth, and changes in surface atmospheric pressure. Tu Yuqiang et al. [12] found that geological conditions such as thick coal seams, high coal grades, relatively closed geological structures, and deep coal seam burial are the main reasons for the high gas content in the mine field, affecting the magnitude of gas emission. In addition, the amount of gas emission is related to atmospheric pressure, coal mining technology, and mining intensity to a certain extent. Yang Tao et al. [3] found that coal seam thickness is the decisive factor affecting the gas emission rate of the mining face. Liu Huimin et al. [13] analyzed the influence of excavation speed and air duct layout on the gas emission rate of the excavation face, and found that the faster the excavation speed, the greater the gas emission rate of the excavation face. At the same time, arranging the air duct on the top side is more conducive to reducing the gas emission rate of the excavation face than on the side.

The East Well of Sihe Mine is a high gas mine with an absolute gas emission of 497.8 m^3/min. It adopts a comprehensive mechanized coal mining method of natural caving and retreat with a long wall and high mining height. To the west of the 4301 working face is the East Fourth Auxiliary Transport Lane, to the north is the 4302 working face, to the south is the 3306 working face, and to the east is the DF_1 major fault. The overall structure of the working face is a low west and high east monocline, on which a series of small and medium-sized folds (anticlines and synclines from west to east) have developed. The anticlines and synclines cause large undulations in the coal seam floor. The coal seam being mined is the 3 # coal seam, with an inclination angle of 1~14 ° and an average of 5 °. The direct top of the coal seam is sandy mudstone with a thickness of 2.43 m, the main top is medium grained sandstone with a thickness of 7.10 m, the direct bottom is sandy mudstone with a thickness of 2.80 m, and the old bottom is mudstone with a thickness of 7.52 m. The original coal gas content is 12 m^3/t. The 4301 working face is the first mining face in the Dongsi Pan area, with a design length of 297.5 meters, a strike length of 2353 meters, a burial depth of 355~504 meters, and an average coal seam thickness of 6.20 meters, elevated whole layer mining, belonging to a large mining height and ultra long working face under high gas conditions. Currently. The influencing factors and laws of gas emission in the excavation face of Sihe Mine are relatively complex, which have a significant impact on coal mine safety production. Therefore, taking the 4301 working face of the East Well of Sihe Mine as the research object, the influencing factors such as coal structure and gas content are analyzed through laboratory simulation experiments, then the influence of gas pressure, excavation speed, and soft layer thickness on the gas emission rate of the excavation working face is explored. The research results can provide reference for on-site gas prevention and control.

2. Analysis of Influencing Factors on Gas Emission in Excavation Face

The characteristics of underground gas emission are similar to the gas desorption characteristics in the laboratory. The gas content and coal structure are the two main controlling factors for the outburst danger in Sihe Coal Mine [14]. Therefore, in the laboratory, the main focus is on analyzing the relationship between gas desorption characteristics, gas content, and coal structure characteristics.

2.1. The Influence of Coal Structure on the Characteristics of Gas Emission

The experiment selected soft coal samples and hard coal samples collected from the same location in the 4301 working face of the East Well Four Plate Area of Sihe Mine, and screened experimental coal samples with a diameter of 0.2~0.25 mm. Adsorption was carried out at pressures of 1.97 MPa and 1.52 MPa, respectively. After 28 hours of adsorption, adsorption equilibrium was reached (adsorption equilibrium time was 28 hours). Then, the coal sample was subjected to free desorption experiments, and the data curve within 30 minutes was recorded, as shown in Figure 1.

From Figure 1, it can be seen that under the same adsorption pressure, the total amount of gas desorption from different coal qualities gradually increases with time and tends to be consistent. During the desorption process, the desorption amount of the soft coal sample and the hard coal sample has the largest difference during the period of 2~15min, which indicates that the softer the coal is, the faster the desorption speed is.

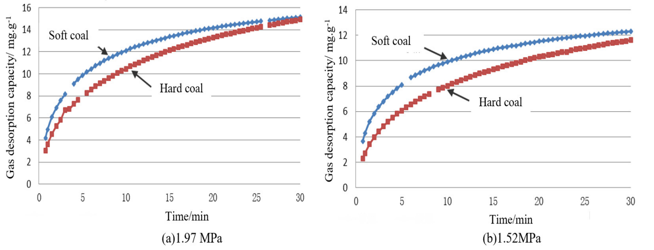


Figure 1. The gas desorption curve

2.2. The Influence of Gas Content on the Characteristics of Gas Emission

The experiment injected CH4 gas into coal samples with particle sizes between 0.25mm and 0.5 mm. After the coal samples reached adsorption equilibrium, the adsorption gas pressures of the coal samples were 0.41 MPa, 1.02 MPa, 1.52 MPa, and 1.92 MPa, respectively. The desorption curves of the four sets of coal samples were fitted to the desorption data using the classical power relationship equation (1), as shown in Figure 2.

$$Q = \alpha \cdot t^{i} \tag{1}$$

Where, Q is gas desorption capacity; t is coal sample desorption time; α and i are Function fitting constants.

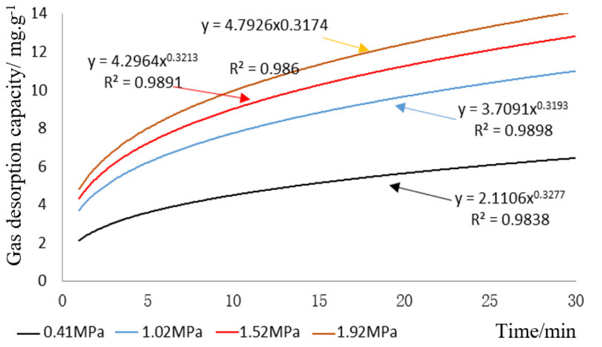


Figure 2. Desorption quantity regular under different pressure

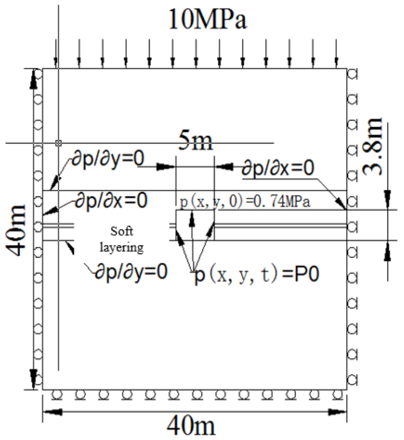
Table 1. Desorption quantity parameter list under different pressure

Pressure	α	i	Q_{10}	Reverse calculates gas content
0.41	2.1106	0.3277	4.6568	10.97
1.02	3.7091	0.3193	7.9469	17.54
1.52	4.2964	0.3213	9.1969	20.27
1.92	4.7926	0.3174	10.2802	21.75

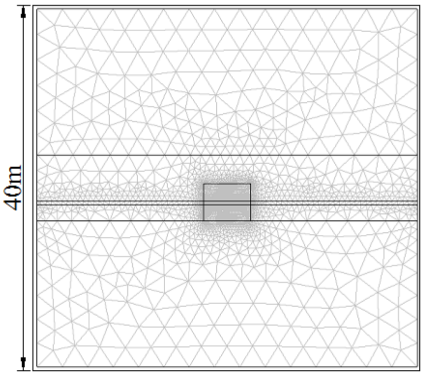
From Figure 2 and Table 1, it can be seen that the influence of gas pressure and gas content on gas desorption is mainly reflected in the difference in gas desorption amount. The amount of gas desorption increases with the increase of gas pressure and gas content.

3. Numerical Simulation of Gas Emission Law in Excavation Face

3.1. Model Construction



(a)The geometric model and the boundary conditions



(b) Model grid

Figure 3. Model construction

The above experiment analyzed the characteristics of the influence of coal structure and gas content on gas emission rate. To investigate the influence of gas pressure, excavation speed, and soft layer thickness on the gas emission rate of the excavation face, COMSOL Multiphysics numerical simulation method was used for research. COMSOL Multiphysics is a professional finite element numerical analysis software based on partial differential equations, which can solve any multi physics field coupling problem. Therefore, this paper utilizes a solid gas coupled flow model for gas flow within coal [15-19]. The coupled flow model is mainly controlled by constitutive equations, stress balance equations, and geometric deformation equations. This paper uses a two-dimensional model for solving calculations. The mesh division of the two-dimensional geometric model and boundary condition model is shown in Figure 3.

3.2. Numerical Simulation Scheme

To analyze the influence of gas pressure, changes in soft layer thickness, and excavation speed on the gas emission rate during tunnel excavation, numerical simulation schemes were developed based on the on-site conditions of the working face, as shown in Table 2 and Table 3.

Table 2. The simulation scheme between thickness of soft layer and gas emission under different gas pressure

Lane location	Soft layering position	Gas pressure/ MPa	Soft layer thickness /m	Excavation speed/ m.d^{-1}
Bottom excavation of coal seam	Middle of the tunnel	0.5	0	8
			0.1	8
			0.3	8
			0.6	8
		0.74	0	8
			0.1	8
			0.3	8
			0.6	8
		0.9	0	8
			0.1	8
			0.3	8
			0.6	8

Table 3. The simulation scheme between tunneling speed and gas emission

Lane location	Gss pressure/MPa	Soft layering position	Soft layer thickness /m	Excavation speed/ m.d^{-1}
Bottom excavation of coal seam	0.74	Middle of the tunnel	0.3	4
				6
				8
				10
			0.6	4
				6
				8
				10

3.3. The Results of Numerical Simulation

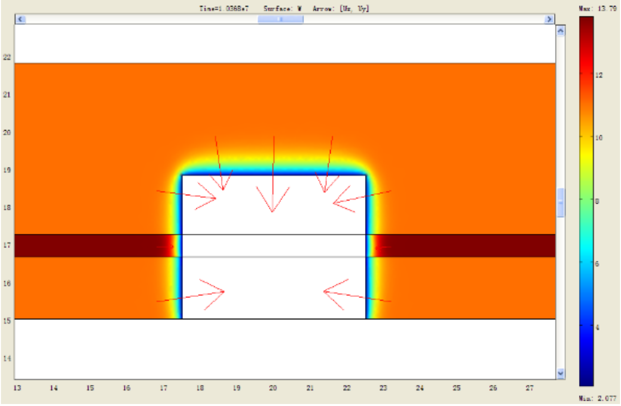


Figure 4. Gas content and gas flow direction around the roadway

(1) Gas pressure and soft layer thickness

By simulating gas pressures of 0.5 MPa, 0.74 MPa, 0.9 MPa and soft layer thicknesses of 0.1 m, 0.2 m, 0.4 m, and 0.6 m, the simulation results of gas emission under different gas pressures and soft layer thicknesses were obtained. Figure 4 shows the cloud map of gas content changes and gas flow direction around the tunnel section when the soft layer thickness is 0.6 m, the coal seam gas pressure is 0.74 MPa, and the gas flow lasts for 120 days (corresponding to 120 days of head-on advancement, 960 m). From Figure 4, it can be observed that the gas flow velocity within the soft layer is lower than that of hard coal.

Figure 5 shows the influence of different gas pressures and soft layer thicknesses on gas emission during excavation. From Figure 5, it can be seen that gas pressure has a significant impact on the amount of gas emitted during excavation. The influence of soft stratification on gas emission is also related to gas pressure, and the greater the gas pressure, the greater the impact of soft stratification on gas emission.

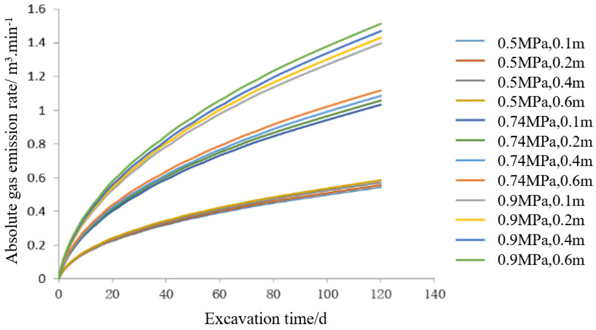


Figure 5. Different gas pressure and thickness of soft layer impact on the gas emission

Figure 6 shows the variation curve of gas emission during the process of soft stratification from 0.1 m to 0.6 m under a gas pressure of 0.74 MPa after 10 days of excavation. From Figure 6, it can be seen that during the process of soft stratification from thin to thick, the gas emission rate also changes from low to high, almost linearly increasing.

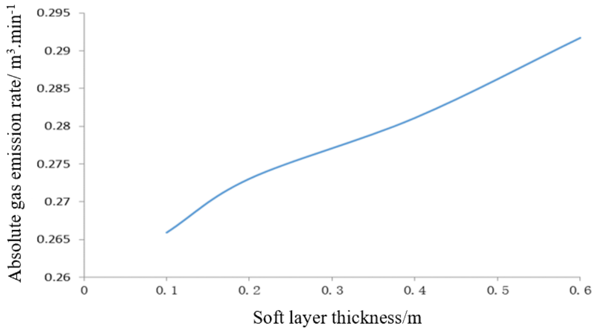


Figure 6. The influence on gas emission with different soft layers under 0.74MPa gas pressure

Figure 7 shows the variation curves of gas emission under 0.74 MPa gas pressure conditions with soft layer thicknesses of 0.1m, 0.2m, 0.4m, and 0.6m. From Figure 7, it can be seen that the variation of soft layer thickness has a relatively small impact on the amount of gas emission during excavation. During the entire excavation process, there is a power function relationship between the gas emission rate and the excavation time (or excavation length), that is $Q = \alpha \cdot t^b$ (a and b are constants, and $b<1$). In addition, the thickness of the soft layer has a significant impact on the gas emission rate during excavation, which is greatly influenced by the adsorption constant of the coal seam. The greater the difference in adsorption constants between soft and hard coal, the more obvious the influence of the soft layer. At the same time, it is also related to the permeability coefficient of the soft coal, which is larger and has a more obvious impact.

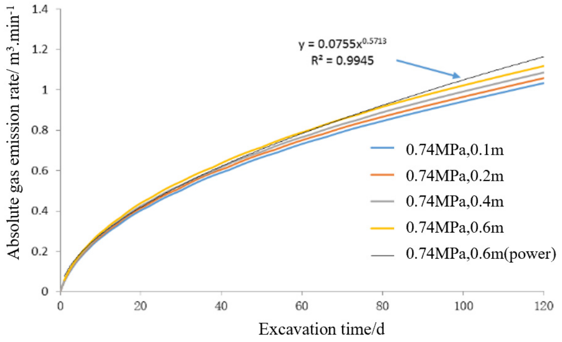


Figure 7. The influence on gas emission with different soft layers under 0.74MPa gas pressure

(2) Excavation speed

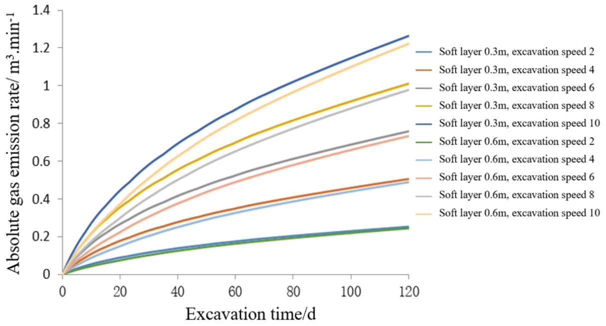


Figure 8. The influence of different tunneling speed on the gas emission

When the gas pressure is 0.74 MPa, simulations were conducted on the gas emission rate at different excavation speeds for soft layer thicknesses of 0.3 m and 0.6 m. The simulation results are shown in Figures 8 and 9.

From Figure 8, it can be seen that excavation speed has a significant impact on gas emission. The faster the excavation speed, the greater the corresponding gas emission. At the same time, the influence of soft layer thickness on gas emission increases with the increase of excavation speed. From Figure 9, it can be seen that the gas emission rate increases linearly with the acceleration of excavation speed.

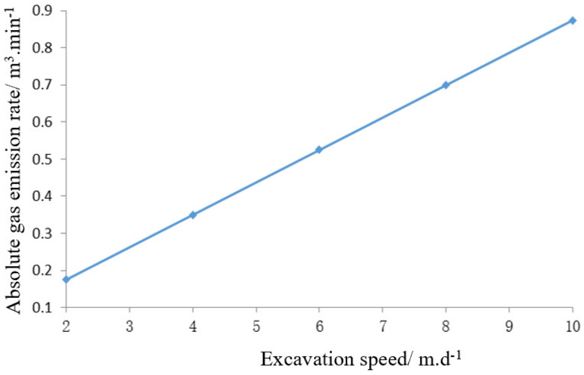


Figure 9. The influence of different tunneling speed on the gas emission

4. Conclusion

(1) For different coal qualities, under the same gas pressure, the gas emission rate increases continuously over time, and the softer the coal quality, the faster the gas emission rate. When the gas content increases, the amount of gas emitted also increases.

(2) The amount of gas emission is affected by gas pressure and excavation speed, and the influence of soft layer thickness on gas emission depends on the magnitude of gas pressure and excavation speed. The greater the gas pressure and excavation speed, the greater the influence of soft layer thickness on gas emission.

(3) The amount of gas emission is positively correlated with the increase of gas pressure, and shows a linear increasing trend with the changes in excavation speed and soft layer thickness.

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