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THE METHOD OF COAL AND GAS OUTBURST RISK ZONES DIVISION BASED ON QUANTITATIVE COUPLING OF GAS AND STRESS

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ABSTRACT: In order to realize the accurate division of coal and gas outburst risk zones, taking Juji Coal Mine as the case study, the method of coal and gas outburst risk zones division based on quantitative coupling of gas and stress is proposed. The results show that the high gas pressure zones are concentrated in the eastern of No.23 mining area, and most of No.26 and No.27 mining area. The vertical stress in the mine ranges from 6 MPa to 36 MPa. The comprehensive weights of gas pressure and stress are determined by AHP-entropy weight method, and the outburst risk comprehensive index Q is calculated accordingly. According to the range of Q, the mine is divided into low risk zone ($Q < 0.5$), medium risk zone ($0.5 \leqslant Q \leqslant 0.75$) and high risk zone ($Q > 0.75$). It has been verified that the drilling cuttings S value in No.26 mining area (high risk zone), No.27 mining area (medium risk zone) and No.211 mining area (low risk zone) is 3.6~4.8 kg/m, 3.2~4.6 kg/m and 3.0~4.4 kg/m, and the initial gas emission velocity q value ranged from 0 to 3.7 L/min, 0 to 0.46 L/min and 0 L/min, respectively.

INTRODUCTION

Coal and gas outburst is one of the most serious disasters in underground coal mine production (Qiu et al., 2022; Zhao et al., 2023). With the increase of mining depth and strength, the coal seam gas pressure and ground stress are increasing, and the coal and gas outburst disaster is becoming more and more serious (Zhang et al., 2022a). How to accurately and efficiently prevent coal and gas outburst disasters has always been the focus of mine disaster research. Accurate division of coal and gas outburst risk zones is the basis of accurate and efficient prevention of outburst disasters (Zhang et al., 2022b).

There are many influencing factors of coal and gas outburst, and how to use these factors to classify and manage the risk of coal seam outburst is important for preventing and controlling coal and gas outburst disasters. Relevant scholars have carried out in-depth research on the accurate division methods of coal and gas outburst risk zones, and put forward various division methods. Wang et al. (2019) performed on outburst risk zone fine division through gas geological analysis. Jia et al. (2023) divided the gas occurrence zones of coal seam in Sichuan Province into three high gas and outburst zones, three high gas zones and one low gas zone according to the tectonic control law and characteristics of coal seam gas occurrence. Li et al. (2020) applied the gas geological unit method to divide the outburst risk zones, and on the basis of fully analyzing the specific conditions of geological structure, gas and structural coal in the mine field, found out their differences and connections in time and space, and divided outburst coal seam or outburst zone within the mine field. Jia et al. (2022) divided gas-geology units by integrating the differences of in-situ stress, geological factors, and gas distribution of each tectonic unit, according to the difference of the bedrock thickness and the CBG distribution in the four tectonic units, combined with the fracture development degree of the coal seam, surrounding rock, and the development degree of deformed coal, the Guhanshan mine field was divided into three gas-geology units. Wang et al. (2018) comprehensively evaluated and predicted the coal and gas outburst risk in the research area through a superposition analysis of the spatial distribution states of three indexes, namely: ground stress, coal structure damage degree, and coal seam gas content. Some scholars have selected some indexes that reflect the outburst risk, such as gas content, gas pressure, structural coal thickness, etc., and divided the outburst risk zones by the critical value of these indexes. Wu et al. (2015) selected the gas content and structural coal thickness as indexes according to the coal seam gas occurrence characteristics and structural coal distribution. When the gas content is more than 5.0 m^3/t and the thickness of structural coal layers in the

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corresponding coal seam is more than 1.2 m, the section is divided to be an outburst risk zone; otherwise, it is divided to be a non-outburst risk zone.

Coal and gas outburst is the result of comprehensive action of ground stress, gas and physical and mechanical properties of coal (Xu et al., 2023; Qiao et al., 2023). The above division methods of coal and gas outburst risk zones mostly use qualitative or semi-quantitative indexes and their critical values to divide the outburst risk zones, but lack quantitative outburst risk comprehensive index. In order to realize the accurate division of coal and gas outburst risk zones, this paper takes No.2_2 coal seam of Juji Coal Mine as the case study, studies the distribution characteristics of gas and stress through data mining and numerical simulation, puts forward outburst risk comprehensive index *Q*, and proposes the method of coal and gas outburst risk zones division based on quantitative coupling of gas and stress.

CASE STUDY

Mine general situation

Juji Coal Mine is located in the southeast of Yongcheng City, Henan Province, China, which is 14 km long in north-south trend and 3 km~5 km wide in east-west trend. The mine area is 61.4 km^2 and the mining depth is -300 m~-1000 m. Juji Coal Mine is a typical coal and gas outburst mine, and the gas and geological types of No.2_2 coal seam to which the mine belongs are extremely complex. There are 9 mining areas arranged in No.2_2 coal seam, which are No.21, No.22, No.23, No.24, No.25, No.26, No.27, No.29 and No.211 mining areas respectively. At present, the main production areas are No.26, No.27 and No.211 mining areas. No.22 coal seam is a stable coal seam that can be mined in the whole area, with a variation coefficient of coal thickness of 24.88% and a mining index of 0.96. The structure of the coal seam is simple, and the northern of the mine suffers from serious magmatic erosion. The depth of coal seam is -600 m~-1050 m, and the coal thickness is 0.80 m~8.86 m, with an average of 2.60 m. After many tectonic movements, fault structures have developed in the mine field. The main faults are near SN, NNE and NE trending normal faults, and there are a group of relatively wide and gentle folds in the south and northwest respectively. Faults, folds and wavy relief constitute the basic characteristics of the geological structure of Juji Coal Mine.

Distribution characteristics of gas pressure

Coal seam gas is one of the main controlling factors of coal and gas outburst in Juji Coal Mine. Studying the distribution characteristics of coal seam gas is the key to accurately divide the outburst risk zone. Coal seam gas pressure is the stress generated by the gas in the pores and cracks of coal seam against the gap wall, and the unit is MPa. Gas pressure is the driving force of gas emission and outburst, and also the sign of coal seam gas content (Cheng et al., 2023). Coal seam gas content refers to the volume of gas contained in the coal body per unit weight, the unit is m^3/t or cm^3/g. According to the Basic Index of Coal Mine Gas Extraction (GB 410-22-2021) of China, gas pressure and gas content can be converted into each other according to formula as following:

$$p = \frac{b\gamma W - abc\gamma - 10\varphi + \sqrt{(b\gamma W - abc\gamma - 10\varphi)^2 + 40b\varphi\gamma W}}{20b\varphi} \tag{1}$$

Where, *p* is the coal seam absolute gas pressure, MPa; *W* is the coal seam gas content, m^3/t; *a* is the gas adsorption constant, which is 24.89 m^3/t; *b* is the gas adsorption constant, which is 0.52 MPa^{-1}; ϕ is the coal porosity, which is 4%; γ is the apparent relative density of coal, which is 1.5t /m^3; *c* is the influence coefficient of coal quality, which is calculated according to formula (2).

$$c = \frac{100 - A_d - M_{ad}}{100} \times \frac{1}{1 + 0.31M_{ad}} \tag{2}$$

Where, A_d is the ash content of coal, which is 11.97%; M_{ad} is the moisture content of coal, which is 1.05%.

Based on the No.2_2 coal seam gas geological map, the test data of coal seam gas pressure and gas content are extracted, the gas pressure is statistically analyzed and data mined, and the gas pressure distribution map is drawn to reveal the gas distribution characteristics. The gas pressure distribution map of Juji Coal Mine is shown in **Figure 1**. The distribution map boundary is the longitude and latitude of the farthest drilling position, the undrilled area is filled with white, and the magmatic erosion area is filled with green.

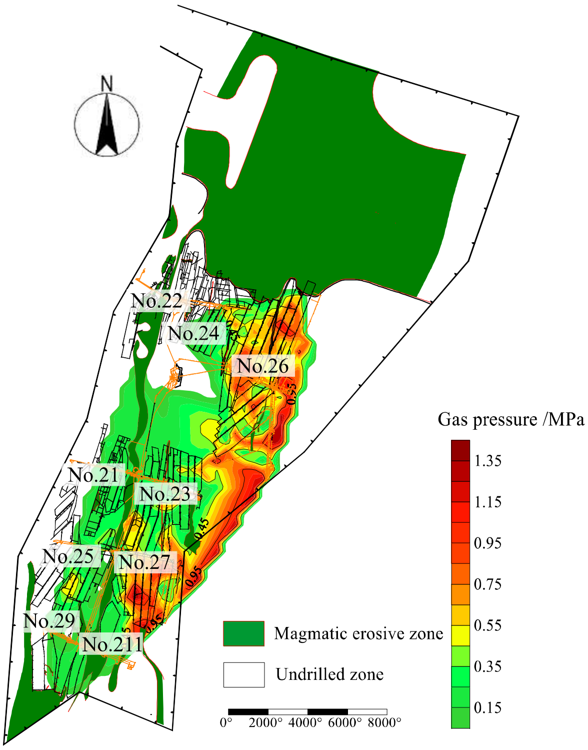

Figure 1: Distribution of gas pressure in No.2$_2$ coal seam of Juji Coal Mine

As can be seen from **Figure 1**, the magmatic erosion area is large, and for the drilled zone, the gas pressure gradually increases from northwest to southeast. the gas pressure in most zones of No.23, No.26 and No.27 mining areas are above 0.6 MPa, and the highest value is located in the south of No.27 mining area, and the highest value is 1.49 MPa. The high gas pressure zone is concentrated in the eastern of No.23 mining area, and most zones of No.26 and No.27 mining areas.

Distribution characteristics of stress

Geological structure is also an important influence factor of coal and gas outburst in Juji Coal Mine. It is very significant for the accurate division of outburst risk zone to study the distribution characteristics of coal seam stress. However, it is difficult to measure the stress in the whole mine. In order to clarify the stress distribution of No.2$_2$ coal seam, taking the actual geological conditions of No.2$_2$ coal seam as the engineering background, according to the mechanical parameters of coal seam in the mine geological report (**Table 1**), FLAC^{3D} is applied to construct the large numerical models of No.2$_2$ coal seam in Juji Coal Mine after appropriate simplification of geological conditions base on Mohr-Coulomb failure criterion and plastic failure model with tensile failure.

Table 1: Mechanical parameters of No.2$_2$ coal seam in Juji Coal Mine

Strata property	Density (kg/m^3)	Bulk modulus (GPa)	Shear modulus (GPa)	Angle of internal friction (°)	Tensile strength (MPa)
Limestone	2360	9.4	6.3	31	4.0
Sandy mudstone	2300	26.0	4.0	31	3.8
Fine sandstone	2900	20.0	7.5	32	5.6
Coal	1400	3.0	1.2	28	1.0
Mudstone	2400	8.0	1.8	34	1.0
medium sandstone	3100	22.0	5.0	31	5.0
gritstone	3200	12.0	9.0	35	6.0
siltstone	2560	1.5	1.0	35	3.6

The size of the numerical model of Juji Coal Mine is X:15446.5 m × Y:6923.8 m × Z:1803.5 m. The X-direction length of the model is consistent with the strike length of the mine, and the Y-direction length is consistent with the dip length of the mine. The maximum difference between the two sides of the model dip is 743 m. The thickness of No.2_2 coal seam in the model is 3 m. Grid measuring points are arranged in the coal seam to record the stress displacement change. The acceleration of gravity is set to 9.8 m/s^2, 0.1 MPa stress load is applied at the top of the model, and fixed boundaries are applied to the bottom and surrounding of the model to limit the movement around and at the bottom. The tectonic stress is mainly in the direction of SN, NNE and NE in the Juji Coal Mine. Therefore, a maximum horizontal stress with an initial stress of 28.2 MPa is applied in the Y-direction and a minimum horizontal stress with an initial stress of 15 MPa is applied in the X-direction. The numerical models of Juji Coal Mine is shown in **Figure 2**.

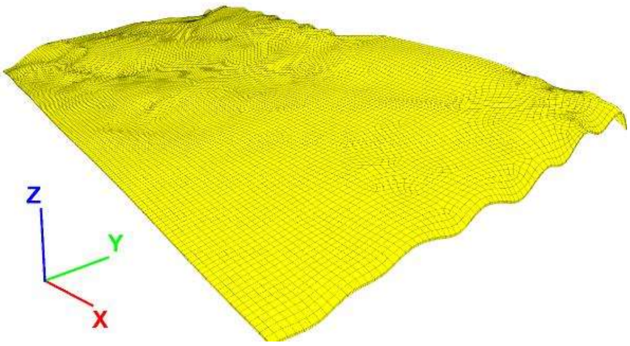

Figure 2: The large numerical models of No.2_2 coal seam

After the above numerical simulation calculation, griddata 2D interpolation is applied to the results, and the vertical stress distribution map is drawn, as shown in **Figure 3**. The vertical stress range of No.2_2 coal seam in Juji Coal Mine is 6 MPa ~ 36 MPa, the high stress zone is located in the eastern of the mine, including the eastern of No.23, No.26 and No.27 mining areas, the low stress zone is distributed in the northwest and southwest, and the central is the stress transition zone. The vertical stress of the mine field increases with the increase of the buried depth of the coal seam. The coal seam in the southwest of the mine is shallow and the vertical stress is low, ranging from 6 MPa to 12 MPa, while the coal seam in the northeast of the mine is buried deep and the vertical stress is high, ranging from 24 MPa to 36 MPa, and the No.26 mining area is in this high stress zone.

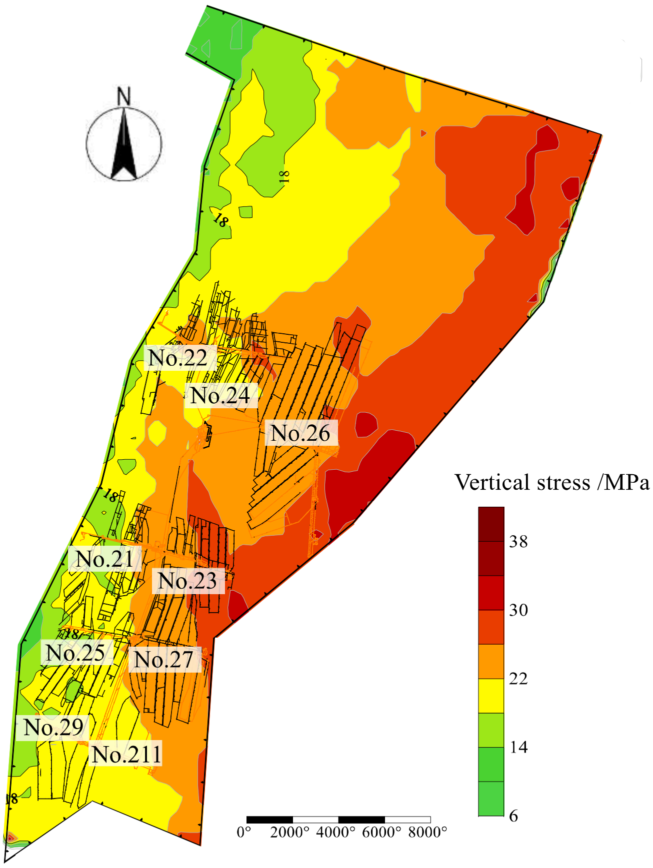

Figure 3: Distribution of vertical stress in No.2_2 coal seam of Juji Coal Mine

COAL AND GAS OUTBURST RISK ZONES DIVISION METHOD

Division method

At present, Juji Coal Mine uses "Double indexes" to divide outburst risk zone, that is, according to measured coal seam gas content and gas pressure and their critical values to divide outburst risk zone. However, stress is also an important factor affecting coal and gas outburst in Juji Coal Mine. The geological structure changes the regional stress field, resulting in different stress concentration degrees of coal seam, which is conducive to the instant release of gas (Guo et al., 2023; Yan et al., 2022). As the power source of coal and gas outburst, gas pressure and stress affect coal and gas outburst in different degrees (Zhang et al., 2022c; Zhao et al., 2022). Therefore, it is difficult to define the outburst risk level only according to the gas index, which is easy to cause the division result of single index is not uniform. To this end, based on the distribution characteristics of coal seam gas pressure and stress in Juji Coal Mine, the gas pressure and stress are quantitatively coupled, and the coal and gas outburst risk zones division method is established.

The Analytic Hierarchy Process (AHP) is a subjective weighting method to determine the weight of indexes. Experts construct a judgment matrix to determine the relative importance of different indexes and finally determine the weight of indexes (Feng et al., 2022). Entropy Weight Method is an objective weighting method which is determined by the judgment matrix composed of the evaluation index value. Information entropy is used to measure the uncertainty or information amount of each index. The greater the information entropy, the higher the uncertainty of the index, so it should be assigned a smaller weight (Liang et al., 2019). AHP-entropy weight method is the index weight determination method which combines AHP and entropy weight method. AHP-entropy weight method synthesizes the expert opinions of AHP and the weight calculation based on data of entropy weight method, which can improve the objectivity and credibility of decision results (Xue et al., 2021). The comprehensive weight calculation formula of AHP-entropy weight method is as follows:

$$w_i = \frac{w_i' w_i''}{\sum_{i=1}^{n} w_i' w_i''} \tag{3}$$

Where, w_i is the comprehensive weight of the ith index, w_i' is the objective weight of the ith index, w_i'' is the subjective weight of the ith index, i = 1, 2, ... n, n is the number of indexes.

Based on the distribution characteristics of gas pressure and stress in Juji Coal Mine, the subjective weight and objective weight of gas pressure and stress are determined by AHP and entropy weight method respectively. The comprehensive weight is calculated by applying formula (3), to couple gas pressure and stress quantitatively, and calculate the outburst risk comprehensive index Q. According to the range of Q, high risk zone, medium risk zone and low risk zone are divided. Accordingly, the method of coal and gas outburst risk zones division based on quantitative coupling of gas and stress is proposed, as shown in **Figure 4**.

As shown in **Figure 4**, after the MinMaxScaler normalization of gas pressure and stress, the AHP is applied to calculate the subjective weights of gas pressure and stress. Using the 1-9 scale method to establish the judgment matrix:

$$\left(a_{ij}\right)_{2\times 2} = \begin{bmatrix} 1 & 3 \\ 1/3 & 1 \end{bmatrix} \tag{4}$$

After the normalization of the judgment matrix, the eigenvector corresponding to the maximum eigenvalue, the eigenvalue λ of the judgment matrix and the consistency index C_I are calculated to carry out consistency test. Finally, the subjective weights of stress and gas pressure are 0.75 and 0.25, respectively. For the data of gas pressure and stress, the information entropy and relative information entropy are calculated respectively, and the objective weights of stress and gas pressure are 0.216 and 0.784, respectively. According to formula (4), the comprehensive weights of stress and gas pressure are 0.452 and 0.548 respectively. According to the gas pressure, stress and the calculated comprehensive weights, the outburst risk comprehensive index Q is calculated, low risk zone (Q < 0.5), medium risk zone (0.5 ⩽ Q ⩽ 0.75), high risk zone (Q > 0.75) are defined to divide outburst risk zones, and draw the coal seam outburst risk distribution and zoning map.

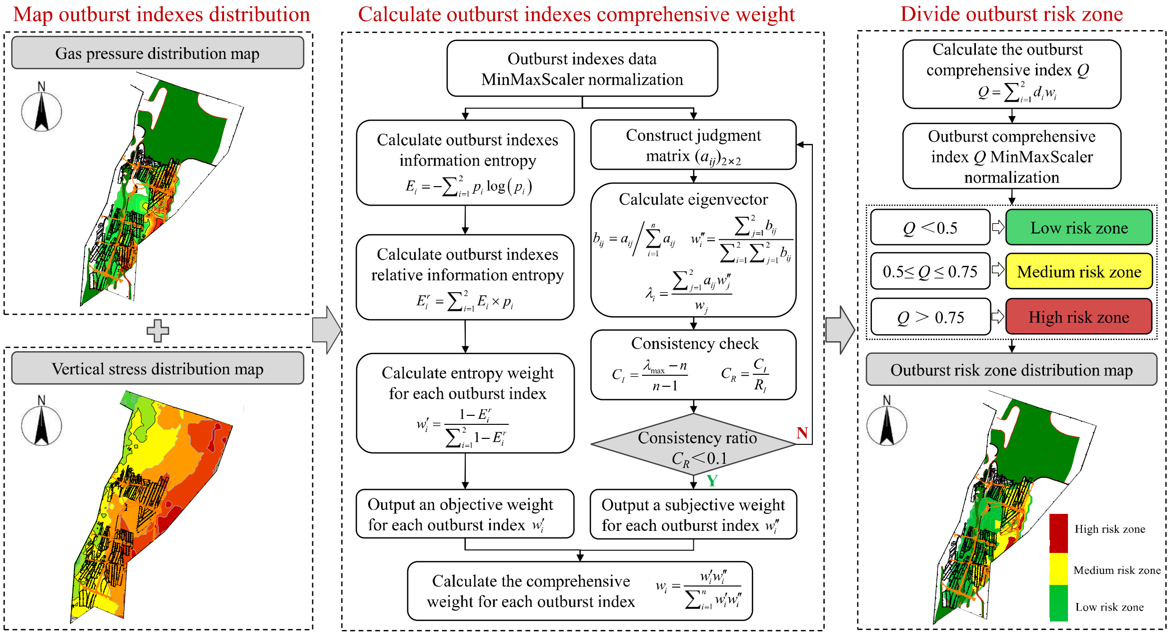

Figure 4: The method of coal and gas outburst risk zones division based on quantitative coupling of gas and stress

Division results

After removing the goaf, undrilled zone and magmatic intrusion zone, considering gas pressure and coal seam stress, the proposed coal and gas outburst risk zones division method based on quantitative coupling of gas and stress is applied to divide the outburst risk zones in Juji Coal Mine. The division results are shown in **Figure 5**.

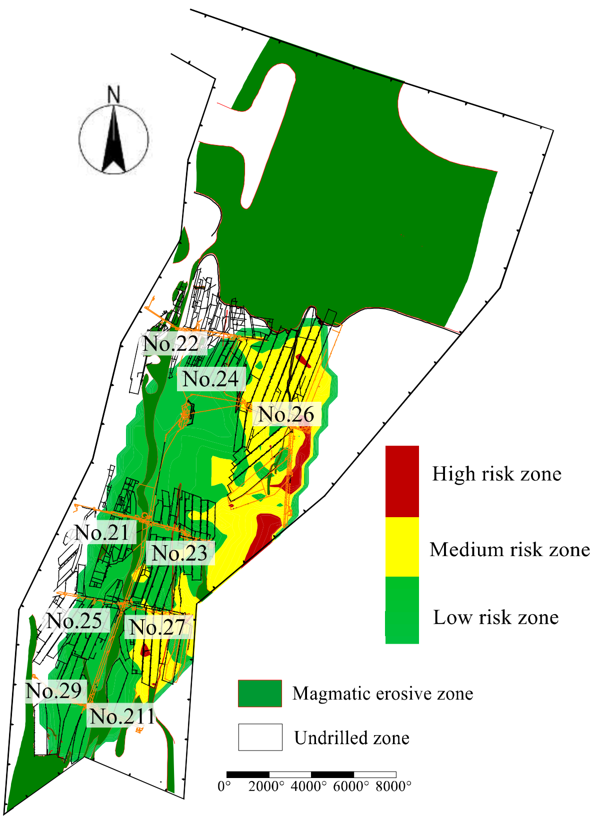

Figure 5: Zoning of outburst risk in No.2$_2$ coal seam of Juji Coal Mine

As shown in **Figure 5**, the comprehensive index *Q* presents an uneven distribution. The *Q* value in most zones is above 0.5, and the *Q* value in some zone of No.23, No.26 and No.27 mining areas is greater than 0.75, and the outburst risk is relatively high. Medium and high risk zones are mainly distributed in the eastern of the mine, most of No.23, No.26 and No.27 mining areas are in the medium risk zone, and a few zones in No.26 and 27 mining areas are in the high risk zone.

DISCUSSION

The test indexes during mining can reflect the degree of outburst risk in a certain area. The drilling cuttings *S* value is the weight of pulverized coal discharged when drilling 1 m, in kg/m. The initial gas emission velocity *q* value is the gas emission amount in the specified length of the drilling hole when the predetermined depth is reached for 2 min according to the specified technical requirements in the coal seam, in L/min. The drilling cuttings *S* value and the initial gas emission velocity *q* value are the test indexes that reflect the ground stress and the coal structural characteristics, and are also the sensitive indexes for predicting coal and gas outburst (Wang et al., 2015). No.26, No.27 and No.211 mining areas are the main production areas of Juji Coal Mine at present. Therefore, the drilling cuttings *S* value and the initial gas emission velocity *q* value in No.26, No.27 and No.211 mining areas during mining are statistically analyzed, as shown in **Figure 6**, to reflect the data characteristics of the test indexes in different outburst risk zones.

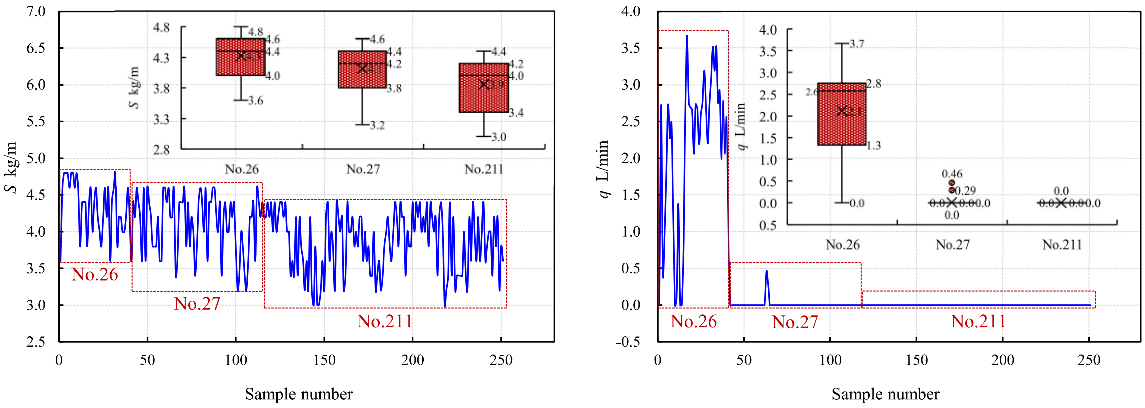

Figure 6: Statistics of test indexes in different outburst risk zones

As can be seen from **Figure 6**, although the drilling cuttings *S* value and the initial gas emission velocity *q* value of are lower than the critical values of 5.8 kg/m and 4.8 L/min, the drilling cuttings *S* value and the initial gas emission velocity *q* value in different outburst risk zones have certain differences. As shown in **Figure 5**, the outburst risk of No.26 mining area is higher, the high risk zones are basically in No.26 mining area, most of No.27 mining area are medium risk zones, and basically all of No.211 mining area are low risk zones. In the No.26 mining area (high risk zone), the drilling cuttings *S* value and the initial gas emission velocity *q* value are higher, and the *S* value ranges from 3.6 to 4.8 kg/m, the *q* value ranges from 0 to 3.7 L/min. The drilling cuttings *S* value and the initial gas emission velocity *q* value in No.27 mining area (medium risk zone) are lower than those in No.26 mining area, and the *S* value ranges from 3.2 to 4.6 kg/m, the *q* value ranges from 0 to 0.46 L/min. The drilling cuttings *S* value and the initial gas emission velocity *q* value in No.211 mining area (low risk zone) are the lowest, and the *S* value ranges from 3.0 to 4.4 kg/m, and the *q* value is 0 L/min. It can be seen that the coal and gas outburst risk zones division method based on quantitative coupling of gas and stress proposed in this paper has certain rationality and applicability.

CONCLUSIONS

The distribution characteristics of gas and stress are studied. In the whole mine, the gas pressure gradually increases from northwest to southeast, and the high gas pressure zone is concentrated in the eastern of No.23 mining area, and most zones of No.26 and No.27 mining areas. The vertical stress range in Juji Coal Mine is 6 MPa ~ 36 MPa.

(2) Coal and gas outburst risk zones division method based on quantitative coupling of gas and stress is established. The comprehensive weights of stress and gas pressure in the whole mine are 0.452 and 0.548 respectively, and those in No.26 mining area are 0.678 and 0.322 respectively. The outburst risk comprehensive index *Q* presents an uneven distribution. The Q value in most zones is

above 0.5, and the *Q* value in some zone of No.23, No.26 and No.27 mining areas is greater than 0.75, which are high risk zones.

(3) The drilling cuttings *S* value and the initial gas emission velocity *q* value in different outburst risk zones have certain differences. It has been verified that the S value of drilling cuttings in No.26 mining area (high risk zone), No.27 mining area (medium risk zone) and No.211 mining area (low risk zone) is 3.6~4.8 kg/m, 3.2~4.6 kg/m and 3.0~4.4 kg/m, respectively; the initial gas emission velocity q value ranged from 0 to 3.7 L/min, 0 to 0.46 L/min and 0 L/min, respectively. It can be seen that the coal and gas outburst risk zones division method based on quantitative coupling of gas and stress proposed in this paper has certain rationality and applicability.

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