DISTRIBUTION OF SPONTANEOUS COMBUSTION AND OPTIMIZATION OF NITROGEN INJECTION LOCATION IN MINE OF FULLY MECHANIZED TOP COAL CAVING FACE

Qi Yun[1, 2], WANG Wei[1, 2], QI Qingjie[3], Ibrar Iqbal*[4], NING Zhangxuan[1], YAO Youli[1]
1. School of Coal Engineering, Shanxi Datong University, Datong Shanxi 037000, China;
2. College of Safety Science and Engineering, Liaoning Technical University, Fuxin Liaoning 123000, China;
3. China Coal Technology Engineering Group, Emergency Research Institute, Beijing, 100013, China;
4. College of Earth Sciences, Guilin University of Technology, Guilin 541004, China

ABSTRACT: *In order to effectively prevent and control the spontaneous combustion of residual coal in the goaf and reduce the waste of nitrogen caused by the setting of nitrogen injection position depending on experience, 1303 fully mechanized coal caving face of Jinniu Mine is taken as a research object, By deploying bundle tube monitoring system in the inlet air side and return air side of the goaf, the change of gas concentration in the goaf is continuously measured, and the distribution area for spontaneous combustion three-zone in the goaf is divided. Based on the division standard of the spontaneous combustion three-zone in the goaf, Based on the "three zones" division standard of spontaneous combustion in goaf, COMSOL Multiphysics5.3 software is applied. The results show that, with the gradual deepening of the nitrogen injection position into the goaf, the impact on the lower limit of the oxidation-combustion zone becomes significant, while the impact on the upper limit of the oxidation-combustion zone is not obvious. The width of the oxidation-combustion zone decreases first and then gradually increases. Numerical calculation suggests that the optimal nitrogen injection position is 40 m from the roof cutting line, and the width of the oxidation-combustion zone is 28 m. Based on the simulation analysis results, nitrogen injection controlling measures have been adopted for the spontaneous combustion of residual coal in the mine of 1303 fully mechanized coal caving face, and coal self-ignition in the goaf has been successfully settled.*
KEYWORDS: fully mechanized top-coal caving face; goaf; oxidized spontaneous combustion zone; numerical simulation; fire prevention and control with nitrogen injection

INTRODUCTION

Coal mine fire is a major disaster that affects the safety of mines. Among them, 85% of the total number of fires in the mine is accounted for by the spontaneous combustion of coal from the goaf[1-3]. The extensive application of fully mechanized top caving technology, while improving the production efficiency of mines and the speed of advancement of the working surface, but has also led to problems such as increased leakage intensity of goaf and excessive residual coal, which increases the probability[4-7]of spontaneous combustion of coal in the goaf. To prevent spontaneous combustion of coal in goaf, spontaneous combustion of the coal seam is used to prevent and extinguish fires in the goaf by injecting nitrogen technology in the process of mining. Domestic and foreign scholars have done a lot of research on nitrogen injection and fire prevention in goaf. Krishna et al[8] used CFD technology to study the change of flow field and designed the nitrogen injection fire-fighting and extinguishing scheme in goaf. Li Zongxiang et al[9]combined the finite element numerical method with the computer graphics technology to simulate the change process of the nitrogen injection and the boundary of the nitrogen injection control area and obtained the negative exponential relationship between the nitrogen injection amount and the boundary of the nitrogen injection control area. Liu Jian et al[10] adopted the Fluent numerical method to optimize the nitrogen injection plan. The reasonable matching of nitrogen injection amount, location of nitrogen injection, and air volume in goaf area were obtained. Zhu Hongqing et al[11] studied the law of spontaneous combustion and temperature rise and the effect of nitrogen injection and fire prevention through the Fluent software. The above literature only focused on nitrogen injection and fire prevention principles and nitrogen injection process, but the effects of coal oxidation and gas emission in goaf were not considered. For this reason, this paper carries out the experimental research on the 1303 fully mechanized caving face of Jinniu coal mine, and the field measurement was carried out to divide the "three-zone" distribution area of spontaneous combustion in the goaf, and the simulation study of the changes of the spontaneous combustion "three-zone" distribution area with the nitrogen injection position through the leakage flow field and oxygen concentration field in the goaf was carried out by using the COMSOL Multiphysics5.3 software. The influence of nitrogen injection location on the width of the oxidation spontaneous combustion zone was analyzed, and the most suitable location of nitrogen injection is optimized. Based on the results of the simulation analysis, it is of great significance to guide the implementation of the nitrogen injection scheme in the field and change nitrogen injection position and nitrogen injection only by the experience setting.

Analysis of the "three zones" of Spontaneous Combustion in Goaf

Overview of 1303 fully mechanized caving mining face

1303 fully mechanized coal caving face in Jinniu coal mine is located in the one mining area of the 1030 level 9+10+11# coal seam. The working face is from the concentrated return airflow tunnel in the east, the west to the boundary of the well field, the 1305 working face in the south, and the 1301 working face in the north. The design length of the working face is 906.6 m, the length of the slope is 90 m, the coal seam thickness is 5.24 m~7.30 m, and the average thickness is 6.17 m. adopting fully mechanized top coal caving mining technology, all the caving methods are used to control the roof of the goaf. The mining height of the working face is 2.9 m, the top coal caving height is 3.3 m, and the ratio of mining and discharging is 1:1.13. The coal seams are well developed and contain 1 to 4 layers of clips. The clips are mainly thin-bedded mudstones with little change in thickness. The dip angle of the coal seam is 8°~14°, with an average of 10°. The exploited coal seam belongs to the type II spontaneous combustion coal seam. The spontaneous combustion period is 21 to 55 days, and the coal dust explosion index is 45.79%, which is explosive.

Field monitoring of "three-zone" of Spontaneous Combustion in Goaf

According to the basic characteristics of the 1303 fully mechanized caving face, the tube monitoring system is laid in the intake and return air lanes, and the GC-2010 gas chromatograph provided by Jinniu coal mine is used to measure the content of all kinds of gases in the goaf with the changing rule of the fully mechanized caving face. Measuring points are arranged at the same time in the intake and return air tunnels. The mutual distance between the measuring points is 20 m, and there are 3 points on each side. The specific layout scheme is shown in Figure 1.

Due to the collapse of the roof of the goaf, it is easy to damage the probe of the measuring point. To prevent the huge impact on the beam tube from the roof falling and the top coal, and the seamless steel tube is used to protect the beam tube when the measurement site is arranged. The tube cable and the temperature measuring wire is fixed into the casing together, and the temperature wire is reserved for a certain length to prevent the fracture of the temperature wire caused by the tension, and the connection between the sleeves is firmly connected with the quick joint. A temperature sensor and a sampling head are installed at each measuring point, and the sampling head is connected with the beam tube, and the temperature sensor is connected with the temperature measuring wire. Using the time of more than two months, the temperature and gas in the goaf of 1303 fully mechanized caving face are measured, and the curve of the oxygen concentration with the advancing degree of the working face is obtained, as shown in Figure 2. The measurement point 6 is not monitored because the beam tube is blocked, and the overall monitoring results are ideal. Because the air leakage velocity is the vector, the field measurement is very difficult. Therefore, it adopts the standard [12-15] of 8%~18%, which is widely used in China at present. The spontaneous combustion zone of the intake air side is 52~109m, and the air backside spontaneous combustion zone. The range is 40~92m.

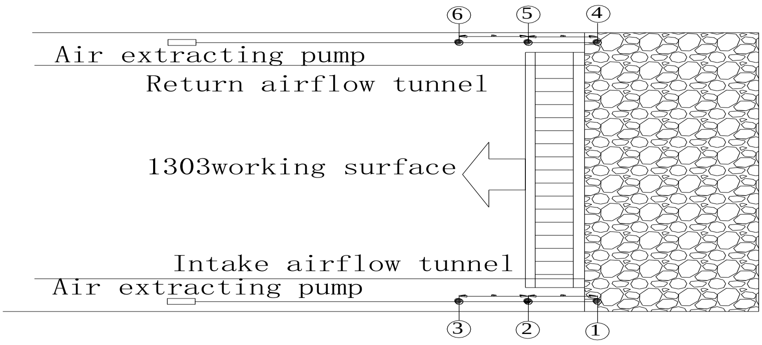


Fig.1 Layout of beam tube and temperature sensor

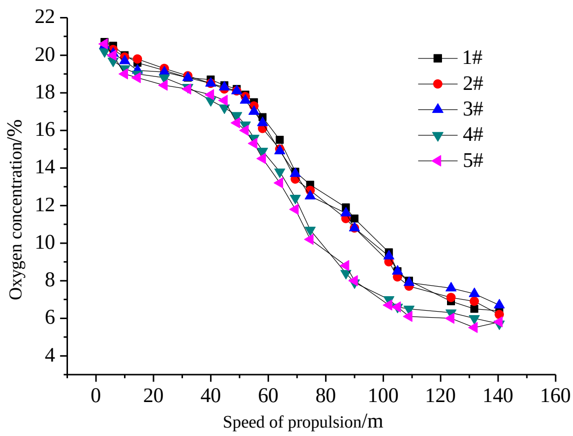


Fig.2 Change curves of oxygen concentration with working face advancing

Calculation model and Solution Conditions

Geometric model

According to the data and actual field measurement of 1303 fully mechanized coal caving face in Jinniu coal mine, the height of the goaf is far less than the plane size. The two-dimensional model is superior to the three-dimensional model in the accuracy and calculation time, and the two-dimensional geometric model of the goaf is established, as shown in Figure 3. The length of the working face is 90m and the width is 7m; the length of the goaf length GL is dynamically changed and the width is 90m; the boundary W1 is the air inlet of the air entry lane, the width is 3m, the W2 is the return air inlet of the return air lane, and the width is 3m, the W3, W4, W7 is the non-acquired solid coal wall in the working face, W5 is the outside protection coal wall of the inlet lane, W6 is the outer protective coal wall of the return air lane. G1 is the boundary of the goaf of the return air lane. G2 is the boundary of the goaf of the intake airflow tunnel, and the G3 of the roof pressure stability area is used to calculate the edge of the area.

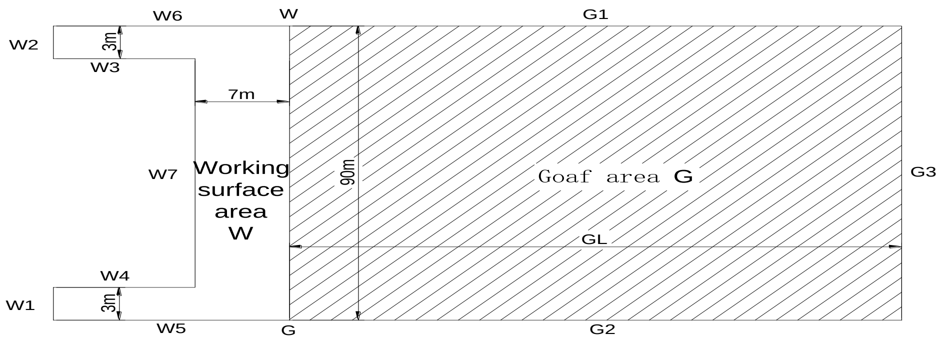


Fig.3 Geometric model of goaf

Mathematical model

Since the establishment of the fluid motion equations must satisfy the basic fluid flow law, when the gas is flowing in the deep part of the goaf at a low velocity, if the gas is set to be incompressible, it can be regarded as the steady problem of the two-dimensional laminar flow. In this case, the energy exchange is not to be considered. Therefore, the flow of the air in the goaf is only needed to meet the momentum conservation equation and the continuity equation [16]. Assuming that the goaf is fully caving and the top and bottom are not gas-permeable, the following control equation can be obtained:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}=\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)-\frac{\partial P}{\partial x}+S_x \qquad (2)$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}=\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)-\frac{\partial P}{\partial y}+S_y \qquad (3)$$

In the formula, u and v are velocity components in the direction of x and y respectively,m/s; ρ is the density of the air in the mine, kg/m^3; t is gas flow time, s; P is the pressure on the fluidmicroelement, Pa; μ is air viscosity coefficient of the goaf, kg/(m·s); S_x and S_y are model related source items.

The source terms of the porous medium model include two parts: the viscous loss term and the momentum loss term[17]. When the fluid moves in porous media, the loss of momentum causes the pressure gradient to decrease, and the loss of pressure gradient is proportional to the rate of a fluid. In a simple homogeneous porous medium:

$$S_i = \frac{\mu}{\alpha_0} v_i + \beta \frac{1}{2} \rho v_j \left| v_j \right| \tag{4}$$

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y} \right) = 0 \tag{5}$$

$$Q_x \cdot \frac{dc}{dx} + Q_y \cdot \frac{dc}{dy} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} - W \tag{6}$$

In the formula, α_0 is the permeability coefficient of the porous medium;$\beta$is the coefficient of inertia resistance; H is the roof caving height, m; Q_x and Q_y respectively indicate the air leakage intensity in two directions of x and y, ($m^3/m^2 \cdot s$)； k is absolute permeability, m^2; c is the mass concentration of oxygen, kg/m^3; D is the diffusion coefficient of oxygen in the coal, m^3/s; W is the oxygen consumption remittance of coal, $mol/(m^3 \cdot s)$.

To make the mathematical model more suitable for the actual situation in the field, the influence of residual coal oxidation and gas emission on the oxygen concentration in goaf is considered, and a model of an oxygen consumption remittance in goaf is constructed:

$$W = -\frac{W(O_2)\cdot H_1}{H} + W(c) \quad (7)$$

$$W(O_2) = \frac{1-n}{n}\cdot\frac{c}{c_0}\cdot\gamma_0\cdot e^{b_0 t} \quad (8)$$

$$W(c) = \frac{n\cdot H\cdot W(CH_4)}{n\cdot H + W(CH_4)}\cdot c \quad (9)$$

$$H_1 = k_1\left[M\cdot(1-\alpha_1) + M_1\right] \quad (10)$$

$$H = \frac{k_p M}{k_p^{(0)} - 1} \quad (11)$$

In the formula, $W(O_2)$ is the oxidative oxygen consumption of coal, mol/(m^3·s); W(c) is the equivalent oxygen consumption intensity, considering the dilution effect of gas emission in goaf, mol/（m^3·s）; $W(CH_4)$ is the amount of gas emission from the goaf, mol/（m^3·s）;γ_0 is the undetermined coefficient of coal oxygen consumption rate, mol/（m^3·s）; c_0 is the oxygen concentration in the new airflow; H_1 is the thickness of coal remains, m; n is the porosity; α_1 is the recovery rate of the working face; k_1 is a loose coefficient; M_1 is the thickness of the upper non - recoverable coal seam, m; k_p is the coefficient of compaction; $k_p^{(0)}$ is initial bulging coefficient; M is mining height, m.

Boundary conditions and calculation parameter settings

When selecting the main calculation conditions and parameters, it is necessary to follow the actual conditions in the field. The entrance boundary of the air entry lane is set as the velocity entrance, the airflow is vertically entered into the entry lane of the intake airflow tunnel, the nitrogen injection port is set as the velocity entrance, and the nitrogen concentration is 97%. The oxygen concentration is 3%, the exit boundary of the goaf is set as free export; the boundary between the working surface and the goaf area is set as the internal condition, and the rest of the surface is set as a wall boundary with a larger seepage resistance. All the walls are non-slip boundary conditions, and the standard wall function method is applied to the near wall of the working surface.

Wall boundary： $E = 0$ (12)

Working surface boundary： $E = R_1 q^2 (l - d)^2$ (13)

In the formula：E is the pressure energy loss of fluid，J；R_1 is ventilation resistance，q is the average air volume of the working surface，m^3/min；l is the length of the working face，m；d is the distance from the intake to the inlet side，m.

The actual measurement of airflow temperature in the intake airflow tunnel is 18.6℃, the actual wind speed of the working surface is 1.62m/s, the average mine air density is ρ =1.225kg/m^3, the air viscosity coefficient at room temperature is μ =1.7894×10^{-5}kg/(m·s), diffusion coefficient of the gas is $D=2.88\times10^{-5}m^3/s$, The looseness coefficient is set to be 1.5. The porosity of the goaf can be obtained from the empirical formula [18] based on the actual situation of the roof falling and bulging.

$$\begin{cases} n = 0.00001x^2 - 0.002x + 0.3(x \le 100) \\ n = 0.2(x > 100) \end{cases} \tag{14}$$

The permeability of the goaf is calculated by porous medium Carman formula [19-20]:

$$k = \frac{D_m^2 n^3}{180(1-n^2)} \tag{15}$$

In the formula: x is the distance from the working surface of the goaf, m. D_m is the average particle size, m.

Determination of Nitrogen Injection amount in Goaf

Before the numerical simulation is carried out, the required nitrogen injection amount is determined according to the actual production conditions and previous experience of the 1303 fully mechanized caving face. The method used this time is to calculate the required amount of nitrogen injection based on the oxygen concentration in the oxidation spontaneous combustion zone. The principle of the amount of nitrogen required for the design of the goaf according to the oxygen concentration of the oxidized spontaneous combustion zone is to dilute the original oxygen concentration in the oxidation temperature rising zone to the oxygen concentration value that meets the inserting requirement, and at this time the amount of nitrogen injection can be calculated by the following form:

$$Q_N = 60Q_0k\frac{C_1 - C_2}{C_N + C_2 - 1} \quad (16)$$

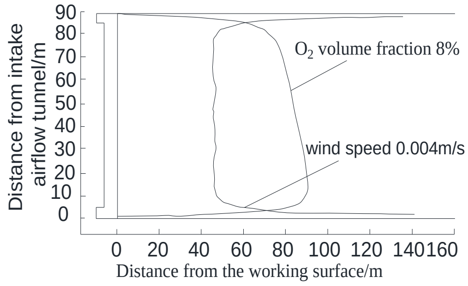
In the formula: Q_N is nitrogen injection, $m^3 \cdot h^{-1}$. K is an additional coefficient, which takes 1.3. Q_0 is the amount of air leakage in the oxidizing rising temperature zone, which takes 3.66 $m^3 \cdot h^{-1}$. C_1 is the average oxygen concentration in the oxidizing rising temperature zone, take 15% according to experience. C_N is the concentration of nitrogen injection, take 97%. C_2 is the concentration of oxygen when the goaf reaches the fire protection requirement, which is 8%. The nitrogen injection amount was calculated to be Q_N=400 $m^3 \cdot h^{-1}$ by substitution formula (16).

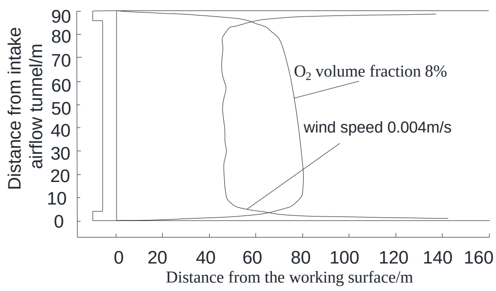
NUMERICAL SIMULATION RESULTS AND ANALYSIS

Numerical Simulation Results

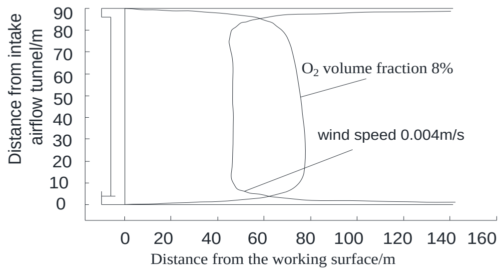
The range of nitrogen diffusion and migration in the goaf will change because of the different positions of nitrogen injection, resulting in changes in the distribution area of the "three-zone" in the goaf. To determine the best position of nitrogen injection, When the nitrogen injection amount is 400 $m^3 \cdot h^{-1}$, the distribution of "three-zone" of spontaneous combustion in goaf is numerically simulated under the conditions of 10, 20, 30, 40, 50, 60, and 70 m spacing between the position of nitrogen injection and the cut-off line. Considering that the flow field parameters of the numerical simulation method are easy to obtain, and have a certain degree of reliability, combined with the characteristics of large gas emission in the goaf of the 1303 fully mechanized caving face, the method is adopted to determine the two classification indexes of the flow velocity and oxygen concentration in the comprehensive goaf, and the three-band distribution is more close to the actual [5,16], That is to say, the isolating lines of wind speed 0. 004 $m \cdot s^{-1}$ and oxygen concentration 8% are determined as the upper and lower limits of the oxidation temperature rising zone.

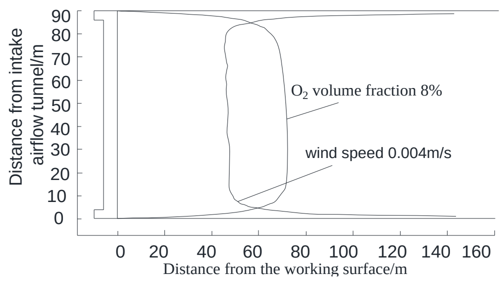
The distribution range of the "three-zone" of spontaneous combustion in goaf under different nitrogen injection positions is obtained by numerical simulation is shown in Figure 4. The red arrow indicates the direction of the flow field, the green line indicates the streamline of the goaf, the red line indicates the equivalent line of the air leakage rate of 0.004 m. s^{-1}, and the black line indicates the equivalent line of the oxygen concentration of 8%. It can be seen that if the location of nitrogen injection is changed, the spontaneous combustion zone of goaf will also have a different distribution trend. With the movement of the nitrogen injection into the deep goaf, the main influence is the oxygen concentration 8% equivalent line, while the variation trend of the air leakage velocity of 0.004 $m \cdot s^{-1}$ is not obvious.



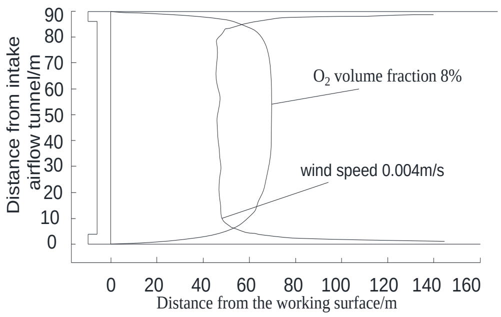


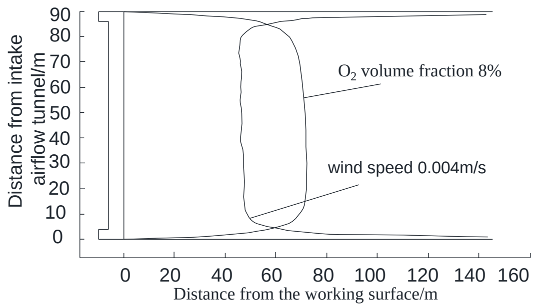
a: Injection nitrogen position from the cut top line 10m b: Injection nitrogen position from the cut top line 20m



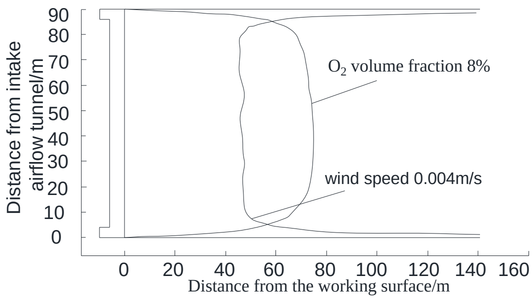


c: Injection nitrogen position from the cut top line 30m d: Injection nitrogen position from the cut top line 40m





e: Injection nitrogen position from the cut top line 50m f: Injection nitrogen position from the cut top line 60m



g: Injection nitrogen position from the cut top line 70m

Fig.4 Goaf oxidized zone distribution under different injection nitrogen position

Analysis of Numerical Simulation Results

The width of the oxidized spontaneous combustion zone in the goaf under the condition of the continuous change of the nitrogen injection position can be obtained by graph 4, as shown in Table 1. It can be seen that the upper limit of the oxidation spontaneous combustion zone is not significantly affected by the position of the nitrogen injection port, and the lower boundary limit of the oxidation spontaneous combustion zone is more significantly affected by the position of the nitrogen injection port. With the location of the nitrogen injection moving away from the cutting line, the width of the oxidized spontaneous combustion zone in the goaf began to shrink, but then gradually increased. Under the conditions of the distance between the injection port and the cutting line is 10, 20, 30, 40, 50, 60, 70 m, the width of the corresponding oxidation spontaneous combustion zone is 44, 35, 32, 28, 26, 28, and 30.6, respectively. The width of the oxidation spontaneous combustion zone is reduced to 75 %、60 %、55 %、48 %、 45 %、48 %、53 % under the condition of non-nitrogen injection, indicating that the nitrogen injection measures in the goaf can effectively reduce the width of the oxidation spontaneous combustion zone.

Tab.1 Distribution of oxidized spontaneous combustion zone in goaf with different nitrogen injection position

Position of nitrogen injection （Distance from crest line） /m	Starting position of oxidation zone /m	Termination position of oxidation zone /m	width /m
10	46.5	90.5	44
20	46	81	35
30	45.5	77.5	32
40	44	72	28
50	44	70	26
60	44.5	72.5	28
70	46	76.6	30.6

Because the location parameters of nitrogen injection will affect the nitrogen injection effect and economic cost, it is necessary to optimize the optimal nitrogen injection amount based on actual production conditions and numerical simulation results. According to Table 1, the relationship between the width of the oxidized spontaneous combustion zone and the position of the nitrogen injection port is plotted using Origin software, as shown in Figure 5. It is known from the diagram that the width of the oxidation spontaneous combustion zone gradually diminishing as the position of the nitrogen injection hole becomes deeper and deeper in the goaf, but the width of the oxidation spontaneous combustion zone begins to increase when the spacing of the nitrogen injection port and the cut top line exceeds 50 m. This is because it is close to the asphyxiated zone in the goaf when the nitrogen injection port is buried in the goaf too deep. The oxygen concentration in the shallower position of the goaf cannot play a very good dilution inserting effect, and the effect of nitrogen injection pressure has greatly limited on the effect of nitrogen injection, so the optimum nitrogen injection position of the goaf should be between the 40~50 m of the distance working face and taking 40 m as the most suitable nitrogen injection position.

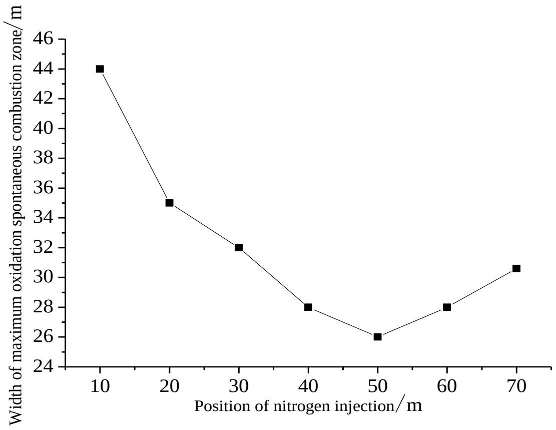


Fig.5 Goaf oxidized zone width with injection nitrogen position change

Application and effect Analysis of Nitrogen Injection Control measures

After consultation with the minerals, according to the numerical simulation results, the nitrogen injection pipeline is embedded inside the goaf of the 1303 fully mechanized caving face, the distance between the nitrogen injection port and the top cut line is 40m, and the nitrogen injection amount is 400m^3/h. The nitrogen source equipment uses the underground mobile molecular sieve nitrogen device, the model number is DT-400, the 4-inch iron pipe is selected as the nitrogen injection pipeline, the nitrogen injection method is mainly for nitrogen injection in the embedded pipe, and the nitrogen injection line is shown in Figure 6.

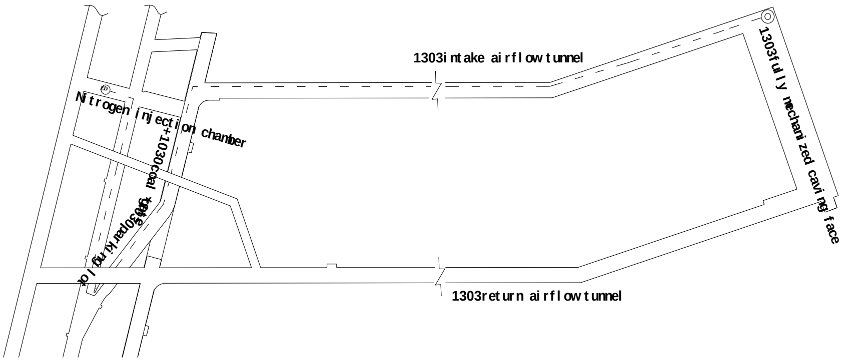


Fig.6 1303 fully mechanized top coal caving face goaf nitrogen injection circuit

After 30 days of nitrogen injection, the gas in the goaf was collected by the existing beam tube monitoring system, and the effect of nitrogen injection on the gas concentration in the goaf was analyzed. The oxygen concentration in the goaf after nitrogen injection was changed as shown in Figure 7. It can be seen from Figure 7 that the width of the oxidation spontaneous combustion zone in the goaf is reduced before nitrogen injection, the width of the oxidation spontaneous combustion zone of the 1# point is 30m, the width of the oxidation spontaneous combustion zone of the 2# point is 29m, the width of the oxidation spontaneous combustion zone of the 3# point is 32m, and the field measured result is consistent with the maximum width 28m of the simulated oxidation spontaneous combustion zone, which verifies the reliability of the numerical simulation results.

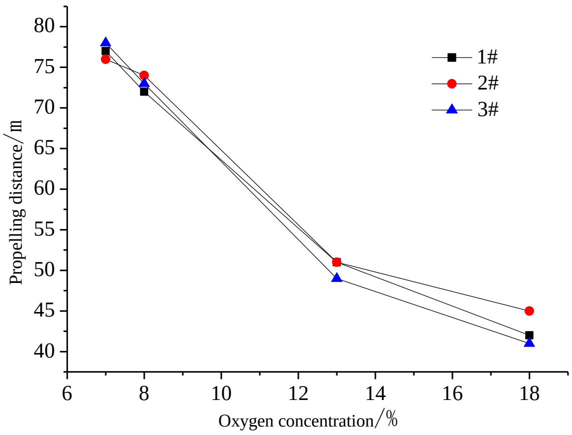


Fig.7 Change of oxygen concentration at each measuring point

To further verify the inerting effect of nitrogen injection on the goaf, considering the dynamic changes of "three-zone" during the mining process of working face, the method of combining two indexes of air leakage velocity and oxygen concentration is used to divide the "three zones" in the goaf after nitrogen injection. Because the leakage velocity cannot be measured in the field, the generally available type is used to estimate the air leakage speed:

$$Q(d_i) = \frac{v_{o_2}(T)(d_{i+1} - d_i)}{c_{o_2} \ln(\frac{c_{o_2}^{i}}{c_{o_2}^{i+2}})} \tag{17}$$

In the formula, $Q(d_i)$ is the speed of air leakage at d_i in goaf, $cm^3/(s.cm^2)$. $v_{o_2}(T)$ is oxygen mass fraction 21%, Oxygen consumption rate of coal body temperature T, $mol/(s.cm^3)$. d_i, d_{i+1} is the distance between any two points of the goaf from the working face, m. c_{o_2} is oxygen concentration in the airflow of the intake tunnel, mol/cm^3. The air leakage velocity calculated by the measured goaf oxygen concentration and formula (15) are used to divide the "three zones" distribution of spontaneous combustion: the width of the spontaneous combustion zone of the air inlet is 33m, and the width of the spontaneous combustion zone of the return air side is 27m. The three-zone of spontaneous combustion divided by the oxygen concentration and the numerical calculation of the air leakage velocity are in agreement with the numerical simulation, which shows that the optimum nitrogen injection parameters determined by the numerical simulation can meet the requirements of the field application.

Based on the consideration of prevention and control of spontaneous combustion in goaf, there is a minimum value for the recovery rate of the working face. The spontaneous combustion zone of the goaf is wider before the nitrogen injection measures are taken, and the actual recovery speed of 2.5 m/d cannot ensure the safe recovery of the working face. The parameters of nitrogen injection are optimized by numerical simulation, and the width of the oxidation spontaneous combustion zone is shortened significantly. The width of the spontaneous combustion zone of the air inlet is shortened by 42%, the width of the spontaneous combustion zone of the return air side is shortened by 48%, and it is satisfied according to the safe recovery speed.

$$v\tau \geq L \tag{18}$$

In the formula, V is the recovery speed of the working face, m/d. τ is the natural ignition period, days. L is the width of the oxidized spontaneous combustion zone, m. The minimum recovery rate is 1.6 m/d under the condition of nitrogen injection, so the working face under the current mining speed is in a safe state. As of January 2018, the 1303 fully mechanized coal caving face had been successfully pushed forward for over 600 meters, and no spontaneous combustion of coal remained in goaf. This indicates that the nitrogen injection control measures for the spontaneous combustion of residual coal in the goaf of 1303 fully mechanized coal caving face are effective according to the numerical simulation results.

CONCLUSION

By measuring the changing trend of the oxygen concentration with the working surface, the "three zones" area of spontaneous combustion in the goaf area of the 1303 fully mechanized coal caving face of Jinniu coal mine is divided, and the distance from the working face of the goaf to the working face is 52~109 m, and the range of the return side from 40 to 92 m from the working face is the oxidation spontaneous combustion zone.

COMSOL software was used to simulate the change law of the "three zones" distribution of spontaneous combustion in goaf under nitrogen injection. It was found that the upper limit of the oxidation spontaneous combustion zone is not significantly affected by the position of nitrogen injection as the position of nitrogen injection position moves to the deep goaf, and the lower boundary limit of the oxidation spontaneous combustion zone is significantly affected by the position of nitrogen injection. The width of the oxidation spontaneous combustion zone begins to shrink and then increases.

Combining the actual production status of the working face and the simulation results, the nitrogen injection position parameters were optimized. When the nitrogen injection flow rate was $400m^3 \cdot h^{-1}$, it was found that when the nitrogen injection port was appropriately extended to the rear of the cutting line 40m, oxygen was diluted and inserted. The gob area has the best effect, and the width of the oxidation spontaneous combustion belt is shortened by about 30 m.

According to the results of the simulation analysis, nitrogen injection measures were taken in the goaf of the 1303 fully mechanized caving face. Field practice showed that the spontaneous combustion of the remaining coal in goaf has been effectively prevented.

Abbreviation

CFD: Computational Fluid Dynamics

GC-2010: model of the gas Chromatograph Model

DT-400:

Declarations

Acknowledgments

The research presented in this paper was supported by the Key Laboratory of Mine Thermodynamic disasters and Control of Ministry of Education (Liaoning Technical University), Huludao, China

Funding

The authors acknowledge the National Natural Science Foundation of China (Grant: 51274113), 12th Five-years National Science and technology support program (Grant: 2011ZX05041-003); General project of scientific research of the education department of Liaoning province (Grant: L2012124)

Availability of data and materials

Competing interests

The authors declare that they have no competing interests.

Reference

[1]LI Zong-xiang, ZHANG Hui-bo, LU Bao-sheng, et al. Research of test and TF1M3D platform simulation on descending airflow fire in mine[J]. Journal of Safety Science and Technology,2018,14(1):30-34.

[2]DUAN Chun-sheng, LI Yan-yun, LI Shi-xiong, et al. Spontaneous combustion three zones determination and fire control technology in goaf under different ventilation volume [J]. Coal Science and Technology, 2015,43(1):62-65.

[3]MA Dong, QIN Bo-tao. Relationship between oxidized spontaneous combustion zone and nitrogen injection quantity in goaf of fully-mechanized top coal caving mining face [J]. Coal Science and Technology, 2016,44(4):78-82.

[4]ZHOU Xin-quan. Proposals on improvement of spontaneous combustion prevention and control in mining goaf and emergency handing capacity [J]. Coal Science and Technology, 2013,41(9):151-153.

[5]ZHOU Xi-hua, BAI Gang, LI Cheng-yu, et al. Study on fire prevention and control technology by controlling air volume on 102 fully-mechanized isolated island caving face of Tianchi Coal Mine[J]. Journal of Safety Science and Technology,2015,11(3):105-111.

[6]CAO Jing-qing, WU Jian-ming, ZHOU Chun-shan, et al. Division of spontaneous combustion dangerous region and determination of nitrogen injection position in goaf of low level top coal caving mining face [J]. Coal Science and Technology, 2017,45(2):89-94.

[7]ZHANG Long, YUAN Shu-jie, ZHU Cheng-tao. Study on distribution of “Three Zones” in

goaf of full mechanized underhand mining face [J]. Journal of Safety Science and Technology, 2013,9(5):67-71.

[8]Krishna Tanguturi, Rao Balusu, Ramakrishna Morla,et al. Effect of buoyancy on methane gas distribution and gas control strategies at tailgate region in a gassy coal mine[C].Proceedings of International Conference on CFD in the Minerals and Process Industries,2013:1-6.

[9]LI Zong-xiang. Numerical simulation and parameter determination of nitrogen injection process in fire prevention and extinguishing in fully mechanized Longwall Top-coal Goaf[J].China Safety Science Journal,2003,13(5):53-57.

[10]GAO Ke, LIU Jian, LIU Yu-jiao. Innovated nitrogen-injection project and numerical simulation in gob at steep inclined fully-mechanized mining face[J]. Journal of Safety and Environment, 2014,14(5):49-53.

[11]ZHOU Hong-qing, LIU Xing-kui. Investigation into spontaneous combustion hazard and numerical simulation of nitrogen injection fire prevention effects in the roof coal[J]. Journal of China Coal Society 2012,37(6):1015-1020.

[12]WU Yu-guo, WU Jian-ming, ZHANG Dong-po, et al. Distribution law of gas and change rule of “three zones” in the goaf of fully mechanized top-coal caving working face under the continuous nitrogen injection [J]. Journal of China Coal Society, 2011,36(6):964-967.

[13]LUO Xin-rong, TANG Guan-chu, LI Ya-wei, et al. CFD mofel based design of both gas drainage and nitrogen injection against fire in goaf [J]. China Safety Science Journal, 2016,26(6):69-74.

[14]Szlazak J. The determination of a co-efficent of longwall gob per-meability[J]. Archives of Mining Sciences, 2001,46(4):451-468.

[15]YIN Xiao-lei, DAI Guang-long, WU Bin, et al. Research on distribution law of “three zones” in goaf of full-mechanized mining face and fire prevention technology under the action of dynamic nitrogen injection [J]. Journal of Safety Science and Technology, 2014,10(10):137-142.

[16]JIANG Zhong-an, LIU Xiang-long, DU Cui-feng, et al. Numerical simulation of goaf sealing and inerting fire-fighting technology for fully mechanical coal faces[J]. Journal of University of Science and Technology Beijing, 2014,36(6):722-729.

[17]WANG Yinhui, AI Xing, ZHAO Tao, et al. Numerical simulation on spontaneous combustion dangerous zone in goaf with high gas and gob-side entry retaining[J].Journal of Safety Science and Technology,2017,13(4):53-58.

SHI Lei. The numerical simulation research of oxygen concentration under the condition of nitrogen injection[D].Huainan, AnHui University of Science and Technology,2013.

[18]WANG Wen-ge, YUAN Kui. Gas drainage affected to spontaneous combustion three zones of mining goaf under the condition of nitrogen injection [J]. Coal Science and Technology,

2014,42(12):75-78,83.

[19]DONG Qiang, ZHOU Xihua, LI Ang, et al. A method for dealing with both gas and fire in low permeability and spontaneous combustion seam full-mechanized mine goaf[J].China Safety Science Journal,2016,26(7):41-45.

[20]ZHOU Xi-hua, MEN Jin-long, LI Cheng-yu, et al. Numerical simulation and the monitoring activities for the spontaneous combustion in the goaf of the fully mechanized cave-mining isolated working face [J]. Journal of Safety and Environment, 2016,16(1):24-28.