Coupling Relation between the Location of Cross-Cut Negative Pressure and Injecting Nitrogen into Coal Mine Goaf

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ABSTRACT: Injecting nitrogen into goaf has been widely adopted for preventing fire hazards in coal mines. In this paper, the coupling relation between different locations of negative pressure of cross-cut drainage and nitrogen injection was investigated. The minefield data collection was carried out by an in situ beam tube system on the intake airway and return airway of the mine goaf. The validated Computational Fluid Dynamics (CFD) model that was secondarily modified by on-site collected data was applied for further research. It is demonstrated that the area of the spontaneous combustion zone generally shows a sharp decline first, then tends to stabilize, and finally has a slight drop and rise with the increasing nitrogen injection time. It is obvious that the location of the negative pressure of cross-cut exerts a significant influence on the optimal nitrogen injection location and time. When the cross-cut is located in the center of the air leakage zone, spontaneous combustion zone, and asphyxiation zone of goaf, the optimal nitrogen injection location and time correspond to the $P_2$ (25 m, 1200 min), $P_3$ (30 m, 120 min), and $P_4$ (35 m, 1800 min), respectively. According to the simulation result, the specific relation between the optimal nitrogen injection point $N(x)$ and the distance from the working distance of the cross-cut ($x$) by Newton interpolation polynomial analysis was figured out and verified that $N(x) = 24.70808 + 0.293356x - 0.001436x^2$. It is hoped that the result can provide scientific guidance for coal mine fire prevention and control with nitrogen injection.

1. INTRODUCTION

Coal self-heating results in a large amount of waste of coal resources\(^1\) and produces noxious fumes, which seriously endanger underground workers.\(^3,4\) Under certain conditions, it often induces methane as well as dust explosion and further leads to devastating catastrophe.\(^5,6\) According to statistics, about 56% of Chinese state-owned coal mines are affected by coal self-heating.\(^7\) In the past few years, with the development of mining equipment and technology, the mining intensity has been gradually strengthened. At the same time, the gas extraction technology has been energetically popularized in gas control. Under the influence of the substantial increase in production efficiency and the gas problem, the residual coal left in goaf and the air leakage to goaf are both rapidly increasing, which cause the coal spontaneous combustion problem in goaf to grow serious.

Coal self-heating is essentially the physical and chemical reactions between coal and oxygen,\(^8,10\) which indicate that coal self-heating and oxygen concentration distribution in goaf are closely related.\(^11-15\) It is reported that when the oxygen concentration in goaf is within a certain critical range, coal spontaneous combustion will be easily triggered.\(^16-18\) Tutak et al.\(^19\) investigated the connection between goaf formed by different types of roof rocks and the high-risk zone of coal self-heating in the Y-type ventilation system. It indicates that the caving rock leads to the different distribution of goaf permeability as well as the range of coal oxidation zone.

Brodny et al.\(^20\) presented simulations of longwall caving working face by a U-type ventilation system; it is found that the oxygen concentration and air velocity decrease along with the distance from mining face. Therefore, reducing the oxygen concentration is a more feasible method to prevent coal self-heating in goaf. At present, the common methods are to minimize the air leakage or to use inert gas to dilute the oxygen in goaf. Recently, Szurgacz et al.\(^21\) developed a new material for preventing coal mine fires that is a mixture of ash, water, and carbon dioxide. Nitrogen is characterized by its high purity, low price, and safety to people and the environment, and it has been extensively adopted in preventing coal mine fires. As early as 1953, the nitrogen formed by the canned liquid nitrogen was adopted to extinguish the coal seam near the shaft station of the Rosslyn mine in the United Kingdom.\(^7\) This method was introduced in China in the 1980s and has become one of the commonly used methods for coal mine fire control and prevention nowadays.
Many kinds of research mainly pay attention to the determination of the various nitrogen injection parameters according to specific conditions of a certain coal mine to achieve the best nitrogen injection effect. Chen et al. applied field test and theoretical research to study nitrogen injection technology for fire prevention in goaf and found that the intake side of the caving goaf is the key area for preventing coal self-heating. Li et al. analyzed the unique law of a Y-shaped ventilation system under nitrogen injection conditions and pointed out that it is more effective to inject nitrogen into the goaf in the inlet side. Based on the relationship between coal spontaneous combustion, oxygen concentration, oxidation zone width, and air leakage strength, Wen et al. quantitatively studied the variation law of relevant parameters of gob after nitrogen injection and obtained the optimum nitrogen injection parameter of controlling coal self-heating in goaf. Zhu et al. designed a non-interval nitrogen injection fire extinguishing technology with a rotating traction mode given the major defects existing in the traditionally buried pipe nitrogen injection fire extinguishing technology, which can keep the nitrogen injection point and the working face moving synchronously and give full play to the best nitrogen injection effect. Zhang et al. investigated coal self-ignition in longwall mining goaf. It determined the best plan of nitrogen injection with a low airflow volume. Luo et al. analyzed the impact of different methane drainage methods, extraction locations, and pumping flow rates with nitrogen injection conditions on the location of coal self-heating areas. The above research results have laid an important foundation for studying the interaction of coal seam gas and coal self-ignition hazard. Furthermore, some literature demonstrates the influence of methane drainage in the high-level lane or overlying drainage tunnel on the coal spontaneous combustion in goaf. Nevertheless, the location and characteristics between the upper tunnel and cross-cut are totally different, which indicate that they will exert disparate influence on coal self-heating in goaf.

In the 8104 fully mechanized mining face, the cross-cut is near the return airway, and the distance between the cross-cut and mining starting line is 110 m. As the working face moves forward, the pressure caused by cross-cut will increase the leakage of air volume into goaf. This situation is quite uncommon in coal mine goaf. On account of the gas emission and coal self-ignition hazard, injecting nitrogen was used to prevent fire in goaf. The location of the cross-cut and the upper lane or overlying drainage lane is quite different. No previous research has investigated the impact of cross-cut negative pressure on nitrogen injection into goaf. In addition, the coupling relationship between the location of cross-cut negative pressure and nitrogen injection has not been proposed. Considering the underground safety, it is urgent to find out the potential relationship between cross-cut negative pressure and nitrogen injection, which will improve the feasibility and economy of fire prevention. However, the negative pressure location will move deep into the goaf as the working face moves forward, leading to the variation of the oxygen concentration field in the goaf. At this time, if nitrogen is pouring into the goaf, the optimal operation location and time will change with the negative pressure location, and there is a coupling relation between them. In this regard, until now, no field experiments or simulations of this subject have been reported. It is too difficult to carry out field tests in goaf due to the fact that researchers cannot enter into the deep goaf. Accordingly, CFD is an effective means to investigate the airflow field in coal mine goaf.

Consequently, this paper established an optimized 3D CFD goaf model based on the field experiment to simulate the dynamic change in the location of goaf negative pressure with different locations of nitrogen injection. The relation between the optimal nitrogen injection location and negative pressure location was determined by simulation and mathematical analysis. It is hoped that the result can provide scientific suggestion for coal mine fire prevention by injecting nitrogen.
2. ON-SITE DATA COLLECTION

The 8104 coal face adopts a broad wall mining technology and a U-shaped ventilation system. The dimension of the mining face is 120 m in width, 430 m in length, and 3.2 m in height. The gas emission amount is 3.2 m³/min. To deal with the methane emission in the working area, the drainage pressure of the cross-cut is used to exhaust gas.

The gas is collected by the field test with the beam tube system. The sampling tubes are placed in the intake airway (1 and 2) and return airway (3 and 4) as shown in Figure 1. To prevent the pipeline and measuring point from being damaged by the caving rock, the protective casing pipe is laid in two lanes, and the bundled tube and temperature measuring wire are put into the protective casing pipe. The tubes are firmly connected by flange joints, and the measuring equipment is wrapped by joist steel. A WRN thermocouple and UT325 thermometer are used to measure the temperature. The inner gas is pumped out by 2X-4 vacuum pumps. The composition and concentration are determined by chromatography. Every other day, the gas sample is sent to the laboratory for analysis. In addition, the portable tester is also adopted to analyze oxygen concentration and temperature every day.

3. BASIC THEORY OF AIRFLOW IN GOAF AND THE MODIFIED CFD MODEL

3.1. Transport Model of Airflow Composition. The oxygen concentration in coal mine goaf is primarily affected by oxygen consumption with residual coal oxidation and attenuation with coal-seam methane emission, which can be determined by the following equation:

\[ \frac{\partial (\rho c)}{\partial t} + \text{div} (\rho u c) = \text{div} (\Gamma \text{grad}(\rho c)) + P_i \]  

where \( c \) represents the volume of specific gas composition \( s \), \( \rho \) represents mass density, and \( \Gamma \) and \( P_i \) mean the diffusion coefficient and rate of mass change, respectively.

The consumption of coal reaction with oxygen causes the decline of \( O_2 \) concentration in goaf. Therefore, coal oxidation at low temperatures is used to present the oxygen consumption as the following equation:\(^38\)

\[ R_{O_2} = AC(O_2)^\alpha \exp(-E/RT) \]  

The value of \( E \) is 12–95 kJ/mol. \( A \) represents the pre-exponential factor. The value of \( \alpha \) is 0.5–1.0. \( R \) and \( T \) are the gas law constant and temperature, respectively, and \( C(O_2) \) is the current \( O_2 \) concentration.

3.2. Modification and Improvement of the CFD Model. Coal mine goaf is filled with caving rocks as well as residual coal, which is like the porous medium. It is reasonable to append the source term as loss of momentum as the following equation:

\[ S_i = -\left( \sum_{j=1}^{3} D_i \mu v_j + \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho v_i v_j \right) \]  

\( i = x, y, z \) 

\[ S_i = -\frac{1}{k} \mu v_i \]  

And \( k \) represents the permeability, which can be calculated from porosity \( n \) by the following equation:

\[ k = \frac{k_0 n^3}{0.241 (1 - n)^2} \]  

To describe the change law of coal mine goaf porosity with caving roof, this paper adopts \( a_0, a_1, b_0, b_1 \) and \( b_1 \) to modify the basic porosity equation as follows:\(^39\)

\[ n(a_0, a_1, b_0, b_1) = \{ 1 - [K_{p,\text{min}} + (K_{p,\text{max}} - K_{p,\text{min}})] \} \times \exp[-a_1(y + b_1)(1 - e^{-a_1(x+b_1)})]^{-1} \times \left( \frac{1 - z}{H} \right) \]  

where \( x \) represents the distance from the open-off cut, \( y \) represents the straight-line distance from headentry toward tailentry, and \( K_{p,\text{max}} \) and \( K_{p,\text{min}} \) represent the maximum and minimum caving and bulking coefficient. The value is determined as 1.6 and 1.1. \( a_0 \) and \( a_1 \) are correction factors with the value of 0.0436 and 0.266. The value of \( \varepsilon \) is 0.358. The value of \( b_0 \) and \( b_1 \) is 0.9 and 18, respectively.

Based on the special condition of the 8104 working face, the field-collected data are used to verify and develop the
traditional model. The detailed value of the above variables is compiled as a UDF file for the further solution in Fluent.

3.3. Detailed Parameters of the Simulation. Based on the field measurement of the 8104 working face, the 3D simulation model is built as shown in Figure 2. The main gate and tailgate are 30 m in length, 4 m in width, and 4 m in height. The bottom of the goaf is a 4 m high residual coal area, and the upper part is a 26 m high rock overburden area. The goaf is built with 537,254 unstructured grid units. The origin of the physical model is set at the joint of the mining face and tailgate. The cross-cut is located in the center of the air leakage zone, spontaneous combustion zone, and asphyxiation zone, respectively. The location of N$_2$ injection is considered to be set near the headentry, and the distance from the working face varies from 20, 25, 30, 35, 40, 45, and 50 m, which are marked as P$_1$–P$_n$, respectively. The volumetric flow rate of the air supplied to the mining working face is set as 830 m$^3$/min, and the air volume of cross-cut is determined as 120 m$^3$/min. The flow rate of nitrogen injection is 1200 m$^3$/h, and the maximum injection time is 1800 min.

The airflow velocity and air leakage of the goaf are relatively low, which accord with the low Reynolds number. It is suitable for turbulence calculation mode. Among many turbulence models, the RNG k-ε model can better deal with flows with low Reynolds numbers and large streamline curvatures. Due to the falling rocks in the goaf, the wind flow streamlines have a large curvature. These are regarded as porous media domains that conform to the RNG k-ε model, which can better describe the real gas flow in the goaf. Hence, the RNG k-ε turbulence model is selected to describe gas migration in coal mine goaf.

The inlet of the intake airway was defined as a velocity-inlet with an airflow speed of 1.5 m/s, the return airway was defined as outflow, and the interface between the mining area and goaf was considered as interior. During the calculation, the operating pressure was 101,325 Pa, and the gravity of 9.8 m/s$^2$ was added in the negative direction of the z axis. This simulation adopted the pressure–velocity coupling and scheme-SIMPLE method for further calculation. The initial iterations were set as 3500–5000, and the convergence tolerance was defined as 10$^{-6}$. The methane–air model was used in the calculation, and the gas mixture composition was CH$_4$, O$_2$, CO$_2$, and N$_2$. The density was defined as incompressible ideal gas, and mixing law was used to determine the specific heat capacity. Other parameters like thermal conductivity, viscosity, and diffusivity were set as 0.0454 w/m·K, 1.72 × 10$^{-5}$ kg/m·s, and 2.88 × 10$^{-5}$ m$^2$/s, respectively.

4. RESULTS AND DISCUSSION

4.1. Results of the On-Site Test. Oxygen concentration is the main reason for coal self-ignition in mine goaf. This paper defines 8–18% of O$_2$ concentration as the real indicator of a high-risk area for coal self-ignition. When the O$_2$ concentration is over 18%, it is regarded as the air leakage zone, and when the O$_2$ concentration is under 8%, it is considered the asphyxiation area.

4.1.1. Analysis of On-Site O$_2$ Concentration in Goaf. Only three sampling points worked normally during the test; hence, we collected the practical O$_2$ concentration as shown in Figure 3.

From Figure 3, when the mining face moves forward, the O$_2$ concentration shows an overall downward trend. When the distance of 1# in the headentry side and the mining face is about 13 m, the O$_2$ concentration becomes 17.9%, which indicates the transformation from heat dissipation to oxidation area. As the distance becomes 58.6 m, the O$_2$ concentration gradually decreases to 7.9%. The result shows that 13–58.6 m is the high-risk area of coal self-ignition. When the distance of 2# in the headentry side and the mining face is about 12 m, the O$_2$ concentration is 17.92%. As it becomes 66 m, the O$_2$ concentration gradually decreases to 7.93%. It indicates that 12–66 m is the high-risk area of coal self-ignition. The above analysis illustrates that the high-risk area of coal self-ignition near the intake airway of goaf is from 12 to 66 m. On the basis of the same analysis of 4#, the high-risk area of coal self-ignition near the return airway of goaf is 9–48 m.

4.1.2. Confirmation of Simulation Accuracy. To verify the accuracy of simulation, the O$_2$ concentrations of the on-site test and simulation are compared as shown in Figure 4.

Figure 4 demonstrates that the simulation results are in line with practical O$_2$ concentration except when the O$_2$ concentration is under 5%. This further illustrates the correctness of the modification and improvement of the numerical model. The validated numerical model is then used for further simulation of the coupling relationship between the location of cross-cut negative pressure and nitrogen injection.

4.1.3. Grid Independence Verification. To ensure mesh independence, tetrahedron grids with total grids of 181,782, 322,632, and 537,254 are adopted in this process.

Figure 5 demonstrates that the O$_2$ concentration under 537,254 grids is in substantial agreement with that of 322,632 grids and 181,782 grids in the three meshed models. The distribution rules of oxygen concentration are evidently not influenced by the grid number, which ensure the mesh independence in solving the problem.

4.2. Nitrogen Injection Results and Analysis. 4.2.1. Dynamic Change of Spontaneous Combustion Zone during Nitrogen Injection. To further explore the change of O$_2$ concentration in the goaf during the nitrogen injection, this paper selects the contour of the simulation result during the nitrogen injection operation in the P$_1$ nitrogen injection port as shown in Figure 6.

The initial steady-state distribution of the O$_2$ concentration indicates that the range of the self-ignition zone on the side of the return airway is obviously expanding to the coal mining face due to the negative pressure of cross-cut. Figure 7
demonstrates that there is an obvious positive effect when the nitrogen injection operation is carried out for just 10 min, and the oxygen concentration distribution of the entire spontaneous combustion zone changes significantly. A similar change trend of oxygen concentration contour is observed in the previous literature that adopts CO2 injection into goaf. The oxygen concentration in most areas is reduced to about 10−13%, especially in the vicinity of the injecting position, where the oxygen concentration drops sharply below 8%. At 60 min, the area of the self-ignition zone on the intake airway side is decreased by about 50%. At 120 min, the length of the self-ignition zone on the inlet side is reduced to about 5 m, which can greatly relieve the workload of fire prevention near the intake airway side. Subsequently, the oxygen concentration field gradually becomes steady, and the range of the spontaneous combustion zone will not change significantly with the increase of nitrogen injection time. When it reaches 1800 min, the area of the self-ignition zone on the return airway side also drops noticeably. It indicates that with the progress of nitrogen injection, the diffusion route of the injected nitrogen gradually penetrates the cross-cut, and the drainage pressure from cross-cut causes injected nitrogen to be discharged from the cross-cut along the minimum path of the resistance. At this time, nitrogen cannot diffuse in all directions of the goaf, resulting in the decline in the nitrogen injection effect. A previous work adopting liquid-nitrogen for coal mine goaf fire control shows the saturation condition with the increase of injection time similarly.

4.2.2. Best Injecting Location and Time. To calculate the best injecting parameters of cross-cut in three different locations of the air leakage zone, self-ignition zone, and asphyxiation zone, the oxygen distribution contour of each simulation stage is recorded, and the optimal nitrogen injection parameters are determined by calculating the area of the self-ignition zone. Subsequently, the relation between the area of the self-ignition zone and the time of nitrogen injection can be obtained as shown in Figure 8.

It can be seen from the curves that with the increasing nitrogen injection time, the self-ignition zone generally shows a
sharp decline first, then tends to stabilize, and after that has a slight drop and rise. When the location of cross-cut is in the air leakage area, it is evident from Figure 8a that the area of the spontaneous combustion zone is the minimum, which is 2767.01 m² with the P₂ nitrogen injection port injecting at 1200 min. Between 0 and 10 min, the nitrogen injection of P₁ to P₅ nitrogen injection points slightly expands the self-ignition zone. After 10–30 min, the area of the spontaneous combustion zone decreases sharply. Between 120 and 300 min, the self-ignition area achieves a basically stable status.
Since the location of the cross-cut is closest to the working face under this condition, it is speculated that the injected nitrogen has already penetrated the cross-cut to form a temporary stable equilibrium state. The closer the nitrogen injection point and the mining face are, the greater the self-ignition area declines, and there exists a positive correlation between them.

Figure 8b shows that as cross-cut locates in the air leakage zone, the area of spontaneous combustion zone is the lowest when the nitrogen injection point is P3 with injecting at 120 min. The area of the spontaneous combustion zone is 2872.19 m², which is 37.7% lower than the initial steady state. Between 0 and 30 min, the self-ignition zone decreases sharply and stabilizes at a later stage. Since cross-cut moves into the self-ignition zone, with the injection of nitrogen, the negative pressure of cross-cut makes nitrogen diffuse to the spontaneous combustion zone quickly and reach a steady state.

Figure 8c demonstrates that as cross-cut moves into the suffocating zone, the area of spontaneous combustion zone is minimum, which is 2551.88 m² as the nitrogen injection point is P4 with injecting at 1800 min. Compared with the range of self-ignition in the initial stable state, it decreases by 34.5%. Between 0 and 30 min, the self-ignition zone decreases sharply. But there will be a slow rising phase between 30 and 300 min. At this time, the cross-cut moves into the deep part of the goaf, the negative pressure in the goaf is relatively high, and the air leakage to the mining face is aggravated. The migration of oxygen toward the goaf causes the range of self-ignition near the working face to increase slightly.

Figure 9. The relation between the oxygen concentration and working face distance in the headentry and tailentry side. a(1) and a(2), b(1) and b(2), and c(1) and c(2) indicate cross-cut in the middle of the air leakage zone, self-ignition zone, and asphyxiation zone.
All the analyses justify an obvious view that the location of the pressure from cross-cut exerts a significant influence on the optimal nitrogen injection location and time. When the cross-cut is in the air leakage zone, self-ignition zone, and asphyxiation zone of goaf, the optimal nitrogen injection locations correspond to the $P_2$, $P_3$, and $P_4$, respectively.

4.2.3. Analysis of the Effect at the Optimal Injecting Location. To analyze the influence of the optimal injecting location on the $O_2$ concentration distribution in the headentry and tailentry side, the curve between oxygen concentration and working face distance is figured out under the optimal nitrogen injection condition as shown in Figure 9.

As can be seen from Figure 9, nitrogen injection caused the decrease of oxygen concentration to varying degrees on both sides of headentry and tailentry, especially on the side of headentry. As presented in a previous work, injecting inert gas will cause the decline of the high-risk area of coal self-ignition. With the increasing distance away from the mining face, the oxygen concentration in the headentry with nitrogen injection first decreases rapidly, reaches the lowest point at the nitrogen injection location, and then shows a slow and small rise to a steady concentration. The decline point is about 5 m before the nitrogen injection location, and the steady state is about 10 m after the nitrogen injection location. As cross-cut moves into the air leakage zone, the oxygen concentration on the headentry side drops below 8% at about 22 m away from the working face, which is 66.2% less than that before nitrogen injection. Similarly, as cross-cut moves into the self-ignition zone and asphyxiation zone, this distance is reduced by 52.6 and 41.8%, respectively. It demonstrates that the effect of injecting nitrogen on the suppression of coal self-ignition near the intake airway is more pronounced. Nevertheless, there exists a certain effect on the suppression of the self-ignition area on the return airway side, but the range of reduction is relatively small.

4.3. Determination of the Relation between the Optimal Nitrogen Injection Point and the Location of the Cross-Cut. Since this paper chooses three cases when cross-cut is in the middle of the air leakage zone, self-ignition zone, and asphyxiation zone, three data points are finally obtained as $(1, 25)$, $(20, 30)$, and $(45, 35)$. To further determine the optimal nitrogen injection point and the location of the cross-cut, the Newton interpolation polynomial is adopted for analysis. Newton’s interpolation polynomial is based on the calculation of mean difference, which is defined as follows.

The first-order mean difference between the $x_i$ and $x_{i+1}$ is

$$f[x_i, x_{i+1}] = \frac{f(x_{i+1}) - f(x_i)}{x_{i+1} - x_i}$$  \hspace{1cm} (7)

Recursively, we define the second-order mean difference as

$$f[x_i, x_{i+1}, x_{i+2}] = \frac{f([x_{i+1}, x_{i+2}]) - f([x_i, x_{i+1}])}{x_{i+2} - x_i}$$  \hspace{1cm} (8)

Then, we can get the Newton parabolic interpolation polynomial as

$$N(x) = f(x_0) + f[x_0, x_1](x - x_0) + f[x_0, x_1, x_2](x - x_0)(x - x_1)$$  \hspace{1cm} (9)

Calculated by substituting data, we can obtain $f[x_0, x_1] = 0.2632$, $f[x_0, x_2] = 0.2$, and $f[x_0, x_1, x_2] = -0.001436$.

Finally, we figure out that the relation between the optimal nitrogen injection point $N(x)$ and the distance from the working distance of the cross-cut ($x$) is

$$N(x) = 24.70808 + 0.293356x - 0.001436x^2$$  \hspace{1cm} (10)

To confirm the accuracy of the formula, we select the conditions when cross-cut is located at 30 and 60 m from the working face for simulation to determine the optimal nitrogen injection point. As shown in Figure 10, when $x = 30$ and $x = 60$, the optimal nitrogen injection location is $P_3$ (30 m, 300 min) and $P_4$ (35 m, 1200 min), respectively. On the other hand, according to the formula, the calculation results of the optimal nitrogen injection location are 32.22 and 37.14 m from the working face, which are basically in good accordance with simulation results. Therefore, it can be concluded that the results of the formula are quite accurate and can provide a certain guiding role in the work of nitrogen injection for fire prevention in coal mine goaf.

5. CONCLUSIONS

On-site test and CFD simulations were conducted to explore the coupling relationship between the location of cross-cut negative pressure and nitrogen injection in coal mine goaf. The following conclusive remarks can be drafted:
(1) On-site test collected data are used to modify and develop the traditional model by a UDF file, and the accuracy of the simulation is proved by comparing the collected data and numerical results.

(2) All the analyses justify an obvious view that the location of the negative pressure from cross-cut has a significant influence on the optimal nitrogen injection location and time. When the cross-cut moves into the center of the heat dissipation zone, self-ignition zone, and asphyxiation zone of goaf, the optimal nitrogen injection locations correspond to the P1 (25 m, 1200 min), P3 (30 m, 120 min), and P5 (35 m, 1800 min), respectively.

(3) According to the simulation result, the specific relation between the optimal nitrogen injection point N(x) and the distance from the working distance of the cross-cut (x) was figured out by Newton interpolation polynomial analysis, which is N(x) = 24.70808 + 0.293356x − 0.001436x².

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