Optimization of Technical Parameters of CO₂ Inerting Goaf in 7271 Working Face of Yaoqiao Mine

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Abstract. Aiming at the problem of fire prevention and extinguishment in the 7271 working face of Yaoqiao Mine, the carbon dioxide inerting method was used to establish the influencing factors system, which combining injecting pipeline parameters, mining technical parameters and inerting gas physical parameters. Numerical simulation method was used to study the influence of different gas injection depth and different gas injection volume on the distribution of carbon dioxide flow field in the goaf. The range of gas injection parameters is determined by hierarchical simulation experiment; Taking comparative experiment between parameters obtain the optimal carbon dioxide fire prevention and inerting parameters for the 7271 working face to study injection depth and injection volume. Experiments show that the width of the oxidation zone reduced by 56m after inerting the goaf, and the width of the asphyxiation zone increased by 29m.

1. Introduction
Coal spontaneous combustion prevention technology in goaf mainly includes grouting, gas injection inerting, pressure equalization, and injection resistance materials [1-3]. Among them, the use of inert gas in goaf is a commonly used method in the mining of sublevel mining face. At present, inert gas injection in the goaf commonly use nitrogen and carbon dioxide.

Based on the advantages of the above inert goaf of carbon dioxide, domestic and foreign scholars have studied the parameters of carbon dioxide injection volume and injection mode [7-9]. Li Shizhen's experimental study on the inhibition of coal oxidizing spontaneous combustion by carbon dioxide [10] provides relevant basic data for further revealing the mechanism of carbon dioxide fire prevention, and provides a theoretical basis for the development and application of carbon dioxide fire prevention technology. Wang Guoguo, Deng Jun, and Zhang Xinhai used the numerical simulation method to study the distribution law of spontaneous combustion "three belts" in the gob of the fully mechanized caving face at different positions and different flows of carbon dioxide at normal temperature [11-13]. Song Yimeng deduced the calculation formula of injecting low-temperature carbon dioxide into goaf fire protection based on the calculation formula of injecting nitrogen in goaf, and analogized the parameters such as the location of injection port [14].

In this paper, the experimental method of grading simulation and the experimental method of parameters are proposed. Based on the existing process parameters, the parameters and inerting technique of carbon dioxide inerting for the working surface of Yaoqiao 7271 are studied.

2. General Situation of Mine
The Yaoqiao coalmine is located in the eastern part of the Datun mining area. The main coal seams are No. 7 and No. 8. The mining method is the fully mechanized sublevel caving mining technology. The
production is 4.45 million tons. The coal mine belongs to a low gassy mine and its relative gas emission amount is 0.0169m³/t in 2014. The coal dust is explosive with the volatile matter of 36.07~46.13%. The spontaneous combustion class of coal mine is Class II, and the spontaneous combustion period of the coal seam is 1~3 months.

The No.7271 working face is located in the No.9 west mining area. The strike length is 358m, the prone length is 260m, the average inclination angle of coal seam is 6°, the average thickness of coal seam is 4.9m, the designed mining height is 4.6m, and the coal bulk density is 1.38t/m³. The height of cut coal is 2.5m and the recovery rate is 85%. The prone mining length in the intake airway is about 109m and the angle is 13°; the return airway is about 139m and 8°

3. General Situation Of Mine

3.1. Principle of Carbon Dioxide Fire Prevention and Extinguishing
Under normal temperature and pressure, carbon dioxide is a colorless, slightly acidic, non-toxic gas. It is an inert compound with high chemical stability and can be widely used as fire extinguishing agent. Carbon dioxide inert goaf generally adopts the way of gas injection. Carbon dioxide covers the surface of coal and rock mass, absorbs and transmits the accumulated heat to the whole goaf.

In addition, carbon dioxide is a kind of weak toxic substance, when its content is 3%, it can increase people's breathing by about 2 times; when its content reaches 25%, it can paralyze people's breathing center and cause acidosis. When using carbon dioxide inert goaf, the safety of staff should be considered [15].

3.2. Carbon Dioxide Inerting Goaf Process
The liquid carbon dioxide is gasified into a gaseous state on the well by a gasifier, and is transported to the fire zone through the ground to the pipeline near the underground fire zone, as shown in figure 1. This method is the lowest injection method.

3.3. Index System of Influence Factors of Carbon Dioxide Injection
The establishment of a carbon dioxide inerting index system is shown in figure 2. The main factors include the parameters of injection pipeline, the parameters of mining technology and the physical parameters of inerting gas.

![Figure 1. Schematic diagram of carbon dioxide injection](image-url)
Factors of carbon dioxide injection for fire prevention and extinguishing in goaf

Parameters of injection pipeline
- the depth of gas injection port
- the position of gas injection port
- the height of gas injection port
- the number of gas injection pipelines

Parameters of inerting gas
- gas injection volume
- gas injection pressure
- gas injection components

Parameters of mining technology
- working surface propulsion speed
- coal mining method
- detection method

Figure 2. Carbon dioxide inerting goaf index system

Among them, the parameters of gas injection pipeline include the depth of gas injection port, the position of gas injection port, the height of gas injection port and the number of gas injection pipelines. The parameters of gas injection include gas injection volume, gas injection pressure and gas injection components. The technical parameters of production include the advancing speed of working face, coal mining method and detection method.

4. Parameter Optimization Experiments of Carbon Dioxide Inert Goaf

4.1. Design Scheme of Experiment

In view of the numerous parameters affecting the injection of carbon dioxide, combined with the actual situation of the 7271 working face, in the intake side of the goaf, a gas injection line with a height of 1 m above the ground is used, and a single pipe injects the gas mixture of carbon dioxide and nitrogen.

Based on the actual goaf data of Yaoqiao 7271, 20~100 m is selected to be divided in to 5 levels of injection depth. Since the carbon dioxide enters the goaf and has a safety impact on the working face, it is necessary to analyze and calculate the amount of carbon dioxide leakage in the goaf. The formulas for calculating the volume and flow rate of goaf during single pipe gas injection at the distance between pipe release outlet and working face d are as follows:

\[ q = dKQ_0 \frac{C_1 - C_2}{C_C + C_2 - 1} \]

\( d \), is the distance from the pipe outlet to the working face, m; \( q \), is the pressure injection carbon dioxide fire prevention and extinguishing flow, m³ / h;

\( Q_0 \), is air leakage in oxidation zone of goaf, m³/min; \( C_1 \), average oxygen concentration in oxidation zone of goaf, %;

\( C_2 \), is inert fire prevention index of goaf, whose value is critical oxygen concentration of coal spontaneous combustion, %; \( C_C \), is injected carbon dioxide concentration, %; \( K \), is reserve coefficient, take 1.2.

The air leakage in goaf is \( Q_0=6\) m³/min, \( C_1=10\% \), \( C_2=5\% \), \( C_C=98\% \).

According to the maximum safe injection volume calculated, injection depth and corresponding injection volume were divided into five level, and a comparison table of simulation experimental parameters of graded inerting was obtained, as shown in table 1.

| Injection Depth (m) | Injection Volume (m³) | Comparison Table of Simulation Experimental Parameters |
|--------------------|-----------------------|-------------------------------------------------------|
| 20                 |                       |                                                       |
| 50                 |                       |                                                       |
| 80                 |                       |                                                       |
| 100                |                       |                                                       |
Table 1. Hierarchical simulation experiment parameter comparison table.

| Test | Injection depth (m) | Maximum safe gas injection | Injection volume (m³/h) | Velocity of intake airway (m/s) |
|------|---------------------|---------------------------|-------------------------|-------------------------------|
| 1    | 20                  | 240                       | 200                     | 0.0708                        |
| 2    | 40                  | 480                       | 450                     | 0.1592                        |
| 3    | 60                  | 720                       | 700                     | 0.2477                        |
| 4    | 80                  | 960                       | 900                     | 0.3185                        |
| 5    | 100                 | 1200                      | 1100                    | 0.3892                        |

4.2. FLUENT Model Establishment

The physical model of mining area includes four parts: working face, air inlet and return roadway, goaf and injection pipeline. The dimensions of each part of the model are shown in table 2.

Table 2. The parameter of model size.

| Area            | Value                                      |
|-----------------|--------------------------------------------|
| Goaf            | 150m (depth) × 260m (length) × 30m (height) |
| Working face    | 260m (Oblique length) × 5m (width) × 3m (height) |
| Intake airway   | 50m (length) × 5m (width) × 3m (height)    |
| Return airway   | 50m (length) × 5m (width) × 3m (height)    |
| Pipeline        | 20/40/60/80m/100m (length) × 0.05m (inside diameter) |

4.2.1. Physical model

Yaoqiao 7271 working face has a small inclination, which should not be considered when establishing the model. In order to reduce the number of grids in the upper model of goaf, the non-planned gridding method is applied. The upper mesh of goaf is sparse, and the dense drawing is carried out at the entrance of injection pipe and the entrance of inlet and return air tunnel. Tet/Hybrid should be in goaf, working face and inlet and return air roadway, and TGrid type grid is used to mesh the stope. Figure 3 is the physical model of goaf without pipeline injection.

![Figure 3. Gob area physical model](image)

4.2.2. Model parameter setting

The model includes the energy equation, the Realizable k-ε turbulence model is selected, and the carbon-monoxide-air in the mixture material is selected as the component model.

4.2.3. Boundary condition setting

The volume fraction of carbon dioxide at the gas injection pipe is 98%, the nitrogen concentration is 2%; the wind speed at the inlet of the intake airway is 1.45 m/s, the air fraction is 20% O₂ and 80% N₂. The outlet of return airway is OUTFLOW boundary. The goaf is set as a porous medium area.
4.2.4. Solve the parameter settings
The solver selects the split solver; the discrete format selects second order; the residual convergence is $10^{-6}$. The calculation is monitored by checking the iterative residuals of each variable.

4.3. Analysis of Hierarchical Simulation Experiment Results
The physical model of mining area includes four parts: working face, air inlet and return roadway, goaf and injection pipeline. The dimensions of each part of the model is shown in table 2.

In order to clearly describe the concentration of each component of the gas in the goaf, a z=1m section is established. According to the observation results of the z=1m cross-section oxygen concentration, the parameter range of the carbon dioxide inerting goaf suitable for the Yaoqiao 7271 working face was determined.

The better the carbon dioxide inerting effect, the narrower the oxidation zone in the goaf. As shown in figure 4, the oxygen concentration is indicated by a white line in the picture.

![Figure 4. The graded inerting simulation experiment z=1m cross section oxygen concentration diagram](image)

It can be seen from the oxygen concentration diagram of test 1-3 that as the depth of the injection tube and the amount of gas injection increase simultaneously, the area of the oxidation zone is obviously narrowed. There was no obvious difference in area between the oxidized zone shown in test3 and test 4. In test 5, the injection amount was continuously increased, and when the injection depth was deepened, the area of the oxidation zone became small a litter. Since the width of the oxidized zone combine the depth and the amount of injection, the effect of two parameters needs to be verified by comparison experiments.

4.4. Analysis of Contrast Simulation Experiment Results
Based on the range of injection parameters obtained from graded inerting simulation experiments, four contrast experiment four groups of comparative experiments were carried out to study the effects of injection depth and injection volume on injection results respectively. The control table of experimental parameters is shown in table 3.
Table 3. Parametric comparison control parameter table.

| Test | Injection depth(m) | Injection volume(m$^3$/h) | Velocity of intake airway(m/s) |
|------|--------------------|---------------------------|------------------------------|
| 3-1  | 60                 | 700                       | 0.2477                       |
| 3-2  | 60                 | 900                       | 0.3185                       |
| 4-1  | 80                 | 700                       | 0.2477                       |
| 4-2  | 80                 | 900                       | 0.3185                       |

Figure 5 can be obtained from table 3 according to comparing the parameters. The oxygen concentration of Z = 1m section is shown below.

![Figure 5](image)

**Figure 5.** Comparison between parameters z=1m cross section oxygen concentration map

In the figure 5, the area of the oxidized zone is not easy to measure, and the width of the oxidation zone in the intake airway and the return airway in the goaf, and the horizontal maximum width of the oxidized zone are measured. The results are shown in table 4.

Table 4. Width measurement in oxidation zone.

| Test | The width of intake airway(m) | The width of return airway(m) | the horizontal maximum width(m) |
|------|--------------------------------|-------------------------------|---------------------------------|
| 3-1  | 5                              | 50                            | 94                              |
| 3-2  | 6                              | 7                             | 72                              |
| 4-1  | 8                              | 38                            | 85                              |
| 4-2  | 8                              | 6                             | 62                              |

According to table 4, it was found that the inerting effect was good at an injection depth of 60 m and an injection amount of 700 m$^3$/h.
5. Analysis of the Results of Parameter Optimization
The simulated control experiment without carbon dioxide injection was set up and compared with test 3. The oxygen concentration distribution of Z = 1m section was compared with that in test 6, as shown below.

![Figure 6](image)

**Figure 6.** The control test group z=1m cross-section oxygen concentration distribution map

The results show that the maximum width of oxidation band is 150 m without inerting gas, the width of oxidation band is 94 m after inerting with appropriate parameters, the oxidation band reduced by 56 m and the asphyxiation band increased by 29 m. In the carbon dioxide inerting goaf, when the appropriate parameters are selected, the inerting effect in the goaf is significant.

6. The Analysis of Experiment
When carbon dioxide injection is 700 m$^3$/h and injection depth is 60 m, gas concentration is collected and measured at 60 m (point A) and lower corner (point B) of goaf depth on the side of the return air roadway respectively. The variation curves of oxygen concentration at point A and CO$_2$ concentration at point B with time are drawn as shown in figure. 7.

![Figure 7](image)

**Figure 7.** Gas concentration curve

The concentration of oxygen measured at point A in the figure 7 shows a significant downward trend after injection of carbon dioxide, and then increases to about 4% and stabilizes to about 8%. The concentration of oxygen measured at the measurement point at point A in the figure has a significant downward trend after the injection of carbon dioxide. After falling to about 4%, it starts to rise, and rises to about 8%. It tends to be stable; the carbon dioxide concentration at point B does not change much, but there is a tendency to rise first and then fall, and the conclusions obtained are the same as the numerical simulation results. Therefore, the use of carbon dioxide inerting gob technology can reduce the oxidation zone width of the goaf.
7. Conclusions

(1) Established the indicator system of the inert goaf of carbon dioxide, including many factors of gas injection parameters, gas injection parameters and mining technical parameters.

(2) The numerical simulation method used to carry out the graded simulation experiment, and the parameters of the carbon dioxide inert goaf suitable for Yaoqiao 7271 obtained.

(3) Based on the results of hierarchical simulation experiments, the parameters of carbon dioxide injection in a single tube obtained by comparing the parameters.

(4) Through comparative analysis of numerical simulation test, the oxidation zone of 7271 working face before and after carbon dioxide inerting reduced by 56 m, which proves that the effect of carbon dioxide inerting goaf is remarkable.

(5) The actual inerting experiment of Yaoqiao Mine is in accordance with the experimental results, which is conducive to the prevention and control of spontaneous combustion of coal in goaf.

8. References

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