Optimisation of multisource injection of carbon dioxide into goafs based on orthogonal test and fuzzy comprehensive theory

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ARTICLE INFO

ABSTRACT

Carbon dioxide is a common inert gas used for fire prevention and extinguishing fires in underground coalmines. However, the single pipeline used for carbon dioxide injection has the characteristics of a narrow inerting area, serious gas leakage in the field, and poor control. To address these risks, we herein propose a technique for multisource injection of carbon dioxide and for building up an index system of carbon dioxide injection for fire prevention and extinguishing in goafs by analysing the parameters of the gas injection pipe, mining technique, and physical qualities of the inert gas. In addition, a mathematical multi-pipeline and multisource model is built on the basis of the diffusion model of carbon dioxide injection with a single pipeline. To improve the insertion efficiency of carbon dioxide injection, a parameter optimisation method of multisource injection based on an orthogonal test and the fuzzy comprehensive theory is proposed. Using the orthogonal test and the FLUENT numerical simulation method, the relationship of the mining speed at the working face, gas injection position, height of the pipeline outlet, and gas flow are studied. Furthermore, the optimal injection parameters are calculated using fuzzy comprehensive theory. The application of this model at the No.7271 working face in the Yaoqiao Coalmine shows that the optimal injection parameters are calculated with the gas injection volume being 500 m^3/h, the gas injection depth being 90 m, and the pipeline number being two. After adopting the optimal parameters of carbon dioxide injection, the concentration of oxygen demonstrates an obvious downward tendency, which is the same as the numerical simulation result. In conclusion, the technique for multisource injection of carbon dioxide can effectively reduce the width of the oxidation zone and prevent spontaneous combustion accidents in goafs.

1. Introduction

Spontaneous combustion of coal accounts for more than 90% of coalmine fires and is the main constraint on the safety and production of coal mines. It leads to serious waste of coal resources and even leads to gas explosions [1]. There are some conventional techniques for fire prevention and extinguishing that involve such as mud grouting and fire inhibitors: gel and foam [2, 3]. The mud grouting technology requires plenty of water and soil and is therefore not suitable for use in semi-arid areas. Furthermore, the mud and gel are poor in flow ability and become heavy polluters. Even worse, due to the heaviness of the material, the grouting mud and foam often intrude onto the working face in the fire prone periods, and affect production safety.

Inert gas, such as N_2 and CO_2, is widely used for fire prevention and extinguishing in goafs. It has the advantages of high chemical stability from being an inert chemical compound, rapid inerting at the fire zone,

arriving at the location easier than with mud or colloid, not affecting the normal mining at the working face, being largely pollution-free and offering a range of applications for fire prevention [4]. Compared with N_2, CO_2 has the characteristics of a higher inerting rate, good performance for explosion suppression, higher speed and lower cost [5]. It is also environmentally significant because retention of CO_2 underground could reduce carbon emission to the atmosphere.

As the interior parameters of the goaf are difficult to observe using monitoring devices, numerical simulation has become the main method for studying the airflow fields of goafs [6]. Using the Navier-Stokes equations, a series of fluid motion models have been solved by CFD software [7, 8] and the distribution of inert gas obtained under different inert gas injection experiments [9]. Gas transport under the condition of inert gas injection into a goaf has been studied using a 3D simulation model. A distribution law of spontaneous combustion in '3 zones' of a fully mechanised goaf was studied at different locations and at different

flow rates in the carbon dioxide pipeline at normal temperature [10, 11].

The degree of spontaneous combustion of residual coal is usually judged by the air leakage [12]. Assuming that the airflow in a natural heterogeneous goaf is turbulent, the airflow transport law is predicted by simulating the pressure, velocity distribution and leakage function [13]. Based on the air leakage and seepage equation of heterogeneous porous media, the air flow law, oxygen concentration and CO concentration distribution law was studied in a 'Y' ventilated goaf [14].

The gas injection position is one of the major factors affecting the inerting efficacy of fire prevention in goafs, and the ideal injection sites are located in the oxidation zone or in the transitional zone between the oxidation zone and the heat dissipation zone [15]. Experimental study provided relevant data for revealing the mechanism, as well as a theoretical basis, for the development and application of fire prevention and extinguishing technology using carbon dioxide [16].

Most of the injection parameters of inert gas in goafs are about nitrogen injection technology. Based on the calculation formula of nitrogen injection, a calculation formula for low-temperature carbon dioxide injection and for the parameters of the pipeline outlet position were deduced [17].

Although scholars have carried out extensive research on the use of carbon dioxide for fire prevention and extinguishing, problems involving the law of gas migration and the technological parameters, such as the accuracy and scientificity of the numerical simulation result, could not be confirmed. The theoretical formula is not universally applicable since too many hypothetical conditions are involved. Besides, it only obtains a predicted range of the relevant parameters. Furthermore, a problem of recent carbon dioxide usage in fire prevention and extinguishing technology is that the relationship between the air leakage and the injection volume of the carbon dioxide is hard to determine. A low flow rate of the inerting gas will reduce the effect of fire prevention and extinguishing because the inerting area is too small; however, a high flow rate will cause safety problems while a high concentration of carbon dioxide flows onto the working face. Therefore, in order to maximise fire prevention and extinguishing effect, parameter optimisation is required.

2. Study area

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 involves fully mechanised sublevel caving mining technology. The production is 4.45 Mt/year. This coal mine belongs among low gassy mines and its relative gas emission was 0.0169 m^3/t in 2014. The coal dust here is explosive when the volatile matter reaches 36.07–46.13%. The spontaneous combustion class of this 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 358 m, the prone length is 260 m, the average inclination angle of coal seam is 6°, the average thickness of coal seam is 4.9 m, the designed mining height is 4.6 m and the coal bulk density is 1.38 t/m^3. The height of the cut coal is 2.5 m and the recovery rate is 85%. The prone mining length in the intake airway is about 109 m and the angle is 13°. The return airway is about 139 m and 8°.

3. Analysis

3.1. Inhibition mechanism of carbon dioxide

The relative molecular weight of carbon dioxide (44.01) is heavier than air. The inhibition mechanism and characteristics of carbon dioxide on the oxidation of coal by auto-ignition are mainly reflected as follows:

(1) The role of inerting in the goaf. The carbon dioxide reduces the oxygen concentration and forms an inert space in a goaf [18]. If the oxygen concentration falls to 10% or less, spontaneous combustion can be effectively suppressed.

(2) Adsorption inhibition. The adsorption capacity of coal and rock is: $CO_2 > CH_4 > CO > N_2$. The oxidation reaction of the coal is weakened if the concentration of carbon dioxide increases.

(3) Heat absorption and transmission. The injected carbon dioxide covers the surface of the coal and rock in a goaf. The carbon dioxide quickly absorbs the heat if its temperature is less than the ambient temperature. Then, it transfers the heat to the low-pressure energy region. This ensures that the heat generated by the oxidation reaction of residual coal will not accumulate, and the temperature of coal and rock will not increase significantly.

(4) Positive pressure deoxygenation. The injected carbon dioxide improves the pressure distribution in the goaf, which can reduce the intake air leakage and increase the carbon dioxide concentration.

(5) Isolation of oxygen. The carbon dioxide often accumulates near the floor and forms a protective layer on the coal surface, which can isolate oxygen from coal and squeeze oxygen out. Therefore, the residual coal will not spontaneously ignite in the state of hypoxia. Carbon dioxide is less affected by ventilation and less susceptible to the airflow. Moreover, it is more suitable for the large inclined coal seams than are other fire prevention and extinguishing technologies.

3.2. Index system of carbon dioxide injection

Fig. 1 illustrates the index system of carbon dioxide injection for fire prevention and extinguishing. The main factors (explained in the list below) include the parameters of the injection pipeline, the parameters of the mining technology and the physical parameters of the inerting gas.

(1) Injection depth of the gas pipeline. This is the vertical distance between the pipeline outlet and the working face, which is closely related to the distribution of the '3 zones' in a goaf. If the outlet is located in the heat dissipation zone, the carbon dioxide will move to the working face with the air leakage. Moreover, if the outlet is located in the asphyxiation zone, it is unsuitable for inerting
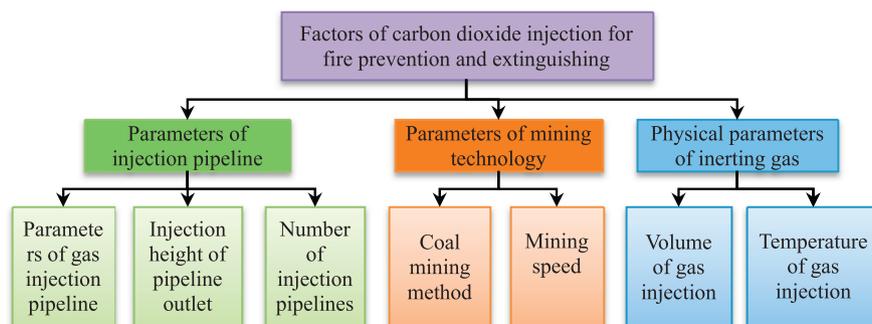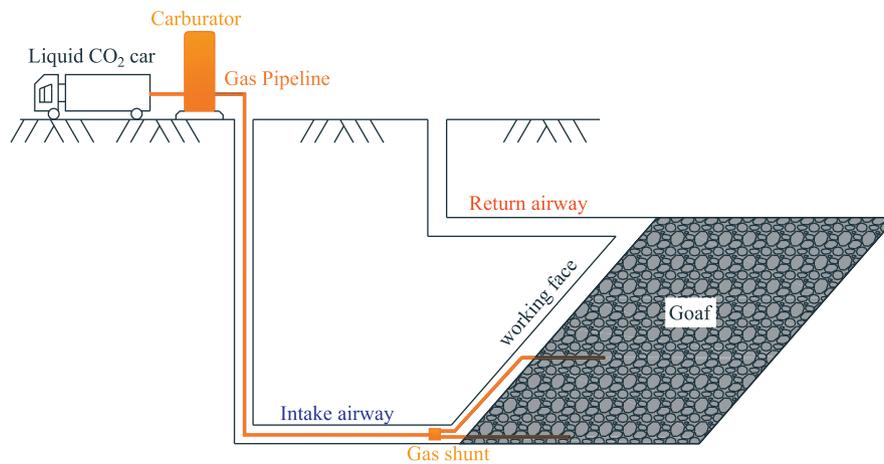

Fig. 1. Factors of index system.

Fig. 2. Schematic diagram of carbon dioxide injection.

effect. Because the inerting gas reduces the width of the oxidation zone, the outlet position should be within the oxidation zone, and the depth near the intake airway side should be greater than on the return airway side.

(2) Injection height of the gas pipeline outlet. Because carbon dioxide is heavier than air, it tends to move downwards. Generally speaking, the greater the injection height is, the larger the carbon dioxide diffusion range will be.

(3) Number of injection pipelines. According to mine ventilation theory, the pressure energy of the intake airway side is higher than the return airway side in a goaf. Using the air pressure difference to achieve the purpose of inerting in the spontaneous combustion zone, the injection pipeline mainly affects the carbon dioxide concentration around, and the pressure energy on, the lower side. The influence range decreases with increase of the porosity.

(4) Coal mining method. The advanced modern mining method and higher coal recovery rate are fundamental approaches to preventing and extinguishing coal spontaneous combustion. The coal mining method is mainly reflected in the layout and management of the physical parameters of the injection pipeline.

(5) Mining speed. Spontaneous combustion of residual coal occurs if spontaneous combustion conditions occur. Mining speed is an important parameter for goaf formation, which is closely related to the width of the spontaneous combustion zone. It mainly affects the injection parameters of carbon dioxide.

(6) Volume of gas injection. This parameter affects the degree of inerting in the goaf. A reasonable injection volume not only effectively reduces the width of the oxidation zone, but also prevents coal spontaneous combustion disasters and other safety accidents; for example, an appropriate volume ensures that the inert gas will not burst onto the workface.

(7) Temperature of gas injection. Carbon dioxide turns liquid under cold conditions and evaporates as gas under normal conditions. The liquid carbon dioxide can be gasified rapidly while absorbing a great deal of heat. However, the technology for its control is an important part of current research.

4. Design

4.1. Injection mode

There are three injection modes.

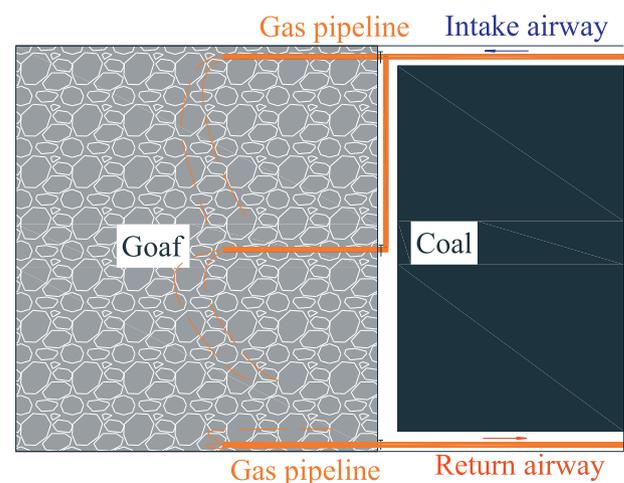(1) Liquid carbon dioxide is directly injected into the fire zone after drilling if the burial depth is shallow.

Fig. 3. Schematic diagram of carbon dioxide injection with three pipelines.

(2) Making a special tanker device (mining vehicle with liquid carbon dioxide), the liquid carbon dioxide is transported to the vicinity of the underground fire zone, and is injected into the goaf by a pipeline.

(3) The liquid carbon dioxide is gasified on the ground by a gasifier, and then transported into a goaf using a long-distance pipeline. Fig. 2 is the schematic diagram of this mode. The injection mode is the most cost-effective option.

4.2. Mechanism of multisource injection techniques for carbon dioxide

The effect of single pipeline injection on the depth of the middle and return airway side is limited. In order to improve the inerting characteristics by using the regional superposition effect, a carbon dioxide injection technology is proposed in combination with multiple pipelines and multiple sources. The multisource injection mode uses multiple pipelines to inject carbon dioxide at the same time, and sets different flow rates at the different positions to increase the injection capacity. Fig. 3 shows a schematic diagram of carbon dioxide injection with three pipelines.

The mechanism of multisource injection techniques of carbon dioxide is as follows.

The air leakage from the airflow inlet at the bottom of the intake airway to the airflow outlet can serve as a ventilating network branch, which forms a ventilation structure parallel with the working surface branch. The pressure energy of the branch changes linearly. The equivalent resistance of the branch can be regarded as a constant since the
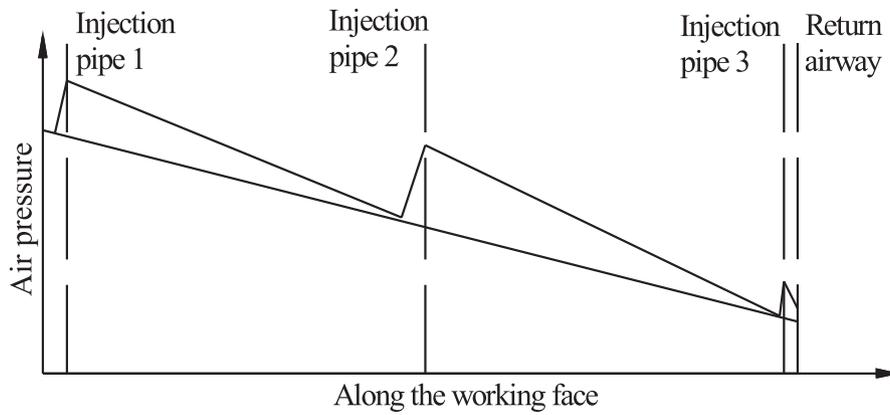
Fig. 4. Curve of the pressure energy distribution in a goaf.

porosity of the goaf is a constant. According to the resistance law, the pressure of the outlet of the pipeline increases while injecting the carbon dioxide, which forms pressure regulation at the outlet of the pipeline. If there is more than one injection pipeline, multiple pressure gradients are formed. Fig. 4 shows the curve of pressure energy distribution in a goaf.

5. Experimental

5.1. Orthogonal test

According to the importance of each parameter, four relatively independent parameters were selected to composite the factors of the orthogonal test. Setting three levels for each factor, an orthogonal table of four factors and three levels was formed, as shown in Table 1.

(1) The injection depth is determined by the three zones of the goaf. Generally speaking, the width of the suffocation zone is about 100 m distance from the working face; therefore, 30 m, 60 m and 90 m were selected.
(2) The more pipelines, the better the gas injection efficiency. However, the desired gas condition is often hard to achieve at the working face. Field application shows that, the gas injection pipelines are easily arranged along the coal pillar at both ends of the working face. Since there are three levels, it is necessary to increase the gas injection pipelines at the middle of the working face.
(3) In general, the air velocity at the working face does not exceed 4 m/s, so 1 m/s, 2 m/s and 3 m/s were selected.
(4) According to the diffusion time of CO_2 in the goaf, the injection volumes of 200 m^3/h, 500 m^3/h and 1000 m^3/h were selected.

According to the three factor and three level orthogonal table, only nine tests are required. The specific parameters of the tests are shown in Table 2.

5.2. Numerical simulation model

(1) Physical model

The physical model of the No.7271 stope is divided into three areas: the working face and roadway, the goaf, and the carbon dioxide injection pipeline. Table 3 illustrates the specific physical parameters, and Fig. 5 shows their physical model and meshing. The area type is set to the fluid type and the goaf is a porous zone. In order to reduce the number of grids, the method of irregular grid partitioning is used to encrypt the grid

Table 3
Parameters of each physical model.

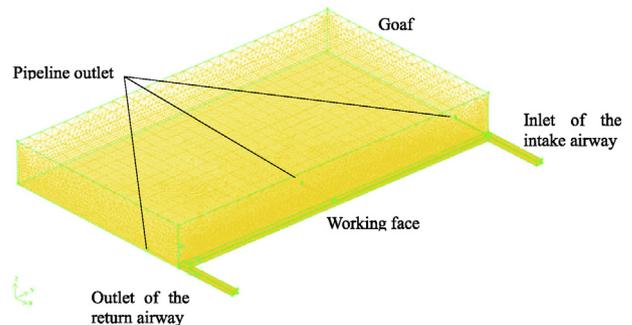| Area	Value
Goaf	150m (depth) ×260m (length) ×30m (height)
Working face	260m (Oblique length) ×5m (width) ×2.5m (height)
Intake airway	50m (length) ×4.8m (width) ×3m (height)
Return airway	50m (length) ×4.8m (width) ×3m (height)
Pipeline	30/60/90m (length) ×1m (inside diameter)

Fig. 5. Physical model and meshing.

Table 1
Factor levels.

Factors	Levels		
	I	II	III
Injection depth/m	30	60	90
Pipeline number/a	1	2	3
Velocity of intake airway/m s^{-1}	1	2	3
Injection volume/m^3 h^{-1}	200	500	1000

Table 2
Initial parameters.

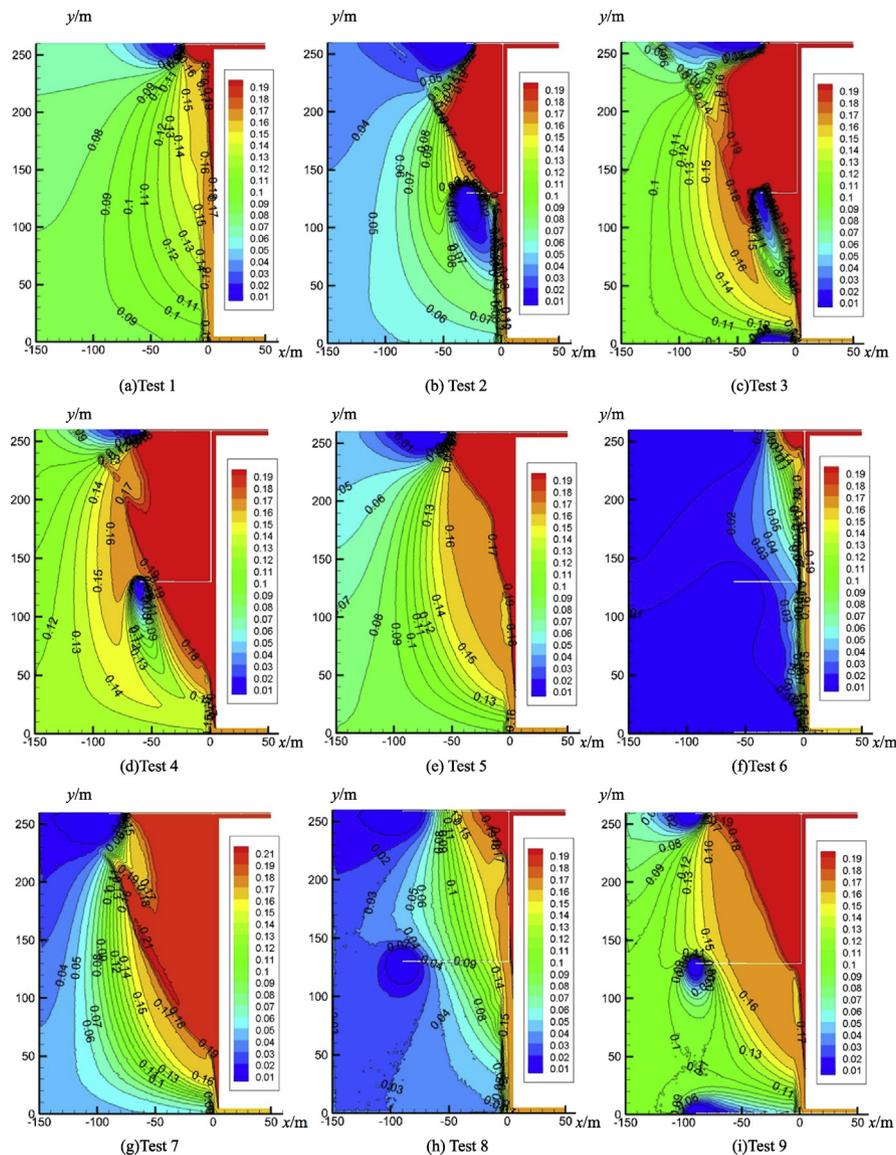| Test	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Injection depth/m	30	30	30	60	60	60	90	90	90
Pipeline number/a	1	2	3	2	1	3	1	2	3
Velocity of intake airway/m s^{-1}	1	2	3	3	2	1	3	1	2
Injection volume/m^3 h^{-1}	200	1000	500	200	500	1000	1000	500	200

Fig. 6. Cloud chart of oxygen concentration distribution (z = 1 m).

around the pipeline and the working face. The element is Tet/Hybrid, the type is TGrid.

(2) Boundary condition settings

The inlet of the intake airway is the Velocity Inlet Boundary. The oxygen fraction is 20% and the nitrogen fraction is 80%.

The pipeline outlet is the Velocity Outlet Boundary. The air velocity of inlet boundary is converted by the air volume and the section of pipeline. The carbon dioxide fraction is 95% and the nitrogen fraction is 5%.

The outlet of the return airway is the Outflow Boundary. The interface between the goaf and the working face is the Interior Boundary.

(3) Control parameter settings

The solver selects the pressure-based method. The solution method adopts the pressure-velocity coupling simple method. The turbulence selects the realisable *k-epsilon* model. The residual convergence is 10^{-6}. The calculation is monitored by checking the iterative residuals of each variable.

5.3. Analysis of the numerical simulation results

The above nine tests were calculated using FLUENT numerical simulation software. Fig. 6 illustrates the oxygen concentration distribution in $z = 1$ section (parallel with the footwall of the physical model). The white line is the injection pipeline. The maximum position of the oxidation zone is located where the oxygen concentration is 10%, as

Table 4
Results of the numerical simulation.

Test	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Maximum position of oxidation zone/m	65	55	122	150	80	12	85	50	125
CO_2 concentration in return airway/%	0.31	1.51	0.96	0.21	0.46	5.75	0.59	0.79	0.5
O_2 concentration in return airway/%	19.54	18.12	18.72	19.57	19.46	17.42	19.25	19.16	19.37

shown in Table 4. Furthermore, the concentration of carbon dioxide and oxygen in the outlet section of the return airway is also shown in Table 4.

The results of the numerical simulation show:

(1) The oxygen concentration near the injection pipeline outlet has maximum decline in the direction of the working face. The decrease of the oxygen concentration in the oxidation zone is greater than that in the heat dissipating zone, and the ratio relation depends on the intensity of carbon dioxide and air leakage. The oxygen concentration at the roof is lower than on the floor (considering the vertical direction).

(2) The air leakage increases with the air volume of the intake airway. Meanwhile, the oxidation zone and the heat dissipating zone become wider. The inlet air velocity of Test 3, 4 and 7 is 3 m/s, and their oxidation zones are wider than in the other tests.

(3) The oxidation zone and the heat dissipating zone get narrower while the injection volume is increasing. The gas injection of Test 2, 6 and 7 is 1000 m^3/h. Test 2 and 6 indicates the limitation of carbon dioxide concentration in the return airway. The injection depth of Test 2 is too shallow, and the concentrated carbon dioxide easily bursts onto the working face with poor sealing of the gas injection. Because the air velocity of Test 6 is small, carbon dioxide fails to be diluted rapidly and easily exceeds the concentration limit of the return airway. In Test 7, the carbon dioxide concentration in the return airway is effectively diluted.

(4) The range of influence of a single pipeline for gas injection is obviously weaker than that of two and three pipelines.

6. Methods

6.1. Fuzzy comprehensive optimisation theory

Suppose $\mathbf{F} = \{F_{ij}\}$, $I = 1,...,m$, $j = 1,...,n$ indicates that the parameter of the m test model corresponds to the set of evaluation factors of n and that the method of relative membership is used to deal with the incommensurability of different dimensions to cause evaluation factors. The values of the relative membership attributes are divided into three categories:

The relative membership degree of the 1st type of evaluation index is,

$$Fr_{ij} = \frac{F_{ij} - \min\limits_{1 \leq i \leq m}\{F_{ij}\}}{\max\limits_{1 \leq i \leq m}\{F_{ij}\} - \min\limits_{1 \leq i \leq m}\{F_{ij}\}} \tag{1}$$

The relative membership value of the 2nd type is,

$$Fr_{ij} = \frac{\max\limits_{1 \leq i \leq m}\{F_{ij}\} - F_{ij}}{\max\limits_{1 \leq i \leq m}\{F_{ij}\} - \min\limits_{1 \leq i \leq m}\{F_{ij}\}} \tag{2}$$

The relative membership value of the 3rd type is one.

$$Fr_{ij} = 1, \left(F_{1j} = F_{2j} =, ..., = F_{mj}\right) \tag{3}$$

Where Fr_{ij} is the relative membership of the set F_{ij} and its range is [0,1]; max{} indicates the maximum value of the set and min{} indicates the minimum value of the set.

The third type is mainly applied to the condition that the attribute values of certain factors are equal.

The following relative membership matrix **Fr** of the fuzzy concept 'superior' is composed of relative membership values of indexes.

$$\mathbf{Fr} = \begin{bmatrix} Fr_{11} & Fr_{12} & Fr_{13} & Fr_{14} \\ Fr_{21} & Fr_{22} & Fr_{23} & Fr_{24} \\ ... & ... & ... & ... \\ Fr_{m1} & Fr_{21} & Fr_{m3} & Fr_{m4} \end{bmatrix} \tag{4}$$

The optimal and the worst values of the evaluation factors are respectively composed of standard superior membership vector $\mathbf{G_R}$ and standard inferior subordinate vector $\mathbf{B_R}$,

$$\mathbf{G_R} = \left(gr_1 \quad ... \quad gr_4 \right)^T = \left(\vee_{i=1}^m Fr_{i1} \quad ... \quad \vee_{i=1}^m Fr_{i4} \right)^T \tag{5}$$

$$\mathbf{B_R} = \left(br_1 \quad ... \quad br_4 \right)^T = \left(\wedge_{i=1}^m Fr_{i1} \quad ... \quad \wedge_{i=1}^m Fr_{i4} \right) \tag{6}$$

Where '$\vee$' indicates the fuzzy number and takes the largest operator and '$\wedge$' represents the small operator.

The following fuzzy partition matrix is defined as follows:

$$\mathbf{U} = \begin{bmatrix} u_{11} & u_{12} & ... & u_{1m} \\ u_{21} & u_{22} & ... & u_{2m} \end{bmatrix} = \begin{bmatrix} u_{1i} \\ u_{2i} \end{bmatrix} \tag{7}$$

Where u_{1i} is subordinate to the superior index and u_{2i} is the inferior index, $\sum_{k=1}^2 u_{ki} = 1, u_{ki} \in [0, 1]$.

The objective function is the minimal sum of the weight difference squared $D(R_i, B_R)$ and $D(R_i, G_R)$ of the m test models.

$$\min f(u_{1i}) = \sum_{i=1}^m \left((D(R_i, G_R))^2 + (D(R_i, B_R))^2 \right) \tag{8}$$

Where $D(R_i, G_R) = u_{1i}\sqrt{\sum_{j=1}^4 [\omega_j(gr_j - Fr_{ij})]^2}$, $D(R_i, B_R) = u_{2i}\sqrt{\sum_{j=1}^4 [\omega_j(Fr_{ij} - br_j)]^2}$ and ω_j is the weight of each factor.

Suppose $\frac{df(u_{1i})}{du_{1i}} = 0$; the optimal fuzzy partition matrix could be calculated as follows.

$$u_{1i} = \left(1 + \frac{\sum_{j=1}^4 [\omega_j(gr_j - Fr_{ij})]^2}{\sum_{j=1}^4 [\omega_j(Fr_{ij} - br_j)]^2} \right) \tag{9}$$

The degrees of influence of the different factors can be evaluated according to the degree of membership u_{1i}.

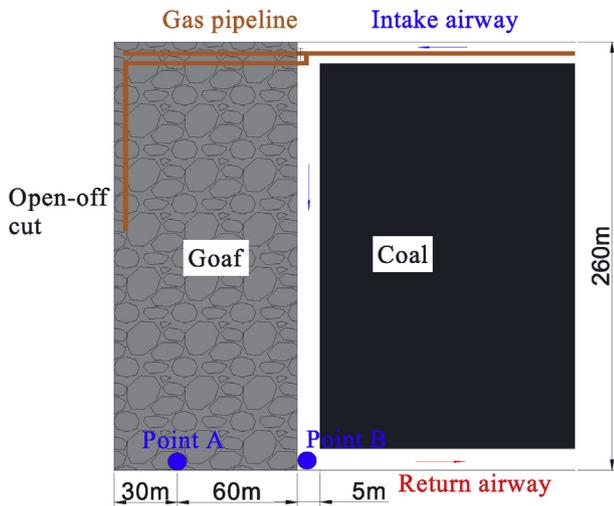**Table 5**
Weight and range of the evaluation factors.

Factors	Maximum position of oxidation zone	Carbon dioxide concentration in return airway	Injection volume	Pipeline number
Weight	0.4	0.2	0.2	0.2
Minimum	65 m	0.03%	200 m^3/h	1
Maximum	150 m	0.1%	1000 m^3/h	3

Table 6
Evaluation result.

Test	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 9
Evaluation result	1.2806	0	0.5836	0.2857	1.2541	0	1.4477	0.6177

Fig. 7. Layout of the pipelines and monitoring locations.

6.2. Optimisation of multisource injection techniques

The main parameters of carbon dioxide injection were determined and are explained below.

(1) The width of the three zones in the goaf. The width of the heat dissipation zone and the oxidation zone should be narrower.
(2) The concentration of carbon dioxide in the return airway. Carbon dioxide will jeopardise the health of the underground workers if the concentration exceeds 1%.
(3) The injection volume and the number of pipelines. The greater the gas injection volume or the higher the number of gas injection pipelines, the better the effect of gas injection.

According to the conditions of each factor, the weight assignment of each evaluation factor is shown in Table 5. The degree of membership of the nine sets of data simulated by orthogonal Eqs (1, 2, 3, 4, 5, 6, 7, 8, 9) is shown in Table 6.

The evaluation result of Test 8 is the best. The gas injection volume is 500 m^3/h, the gas injection depth is 90 m and the number of pipelines is
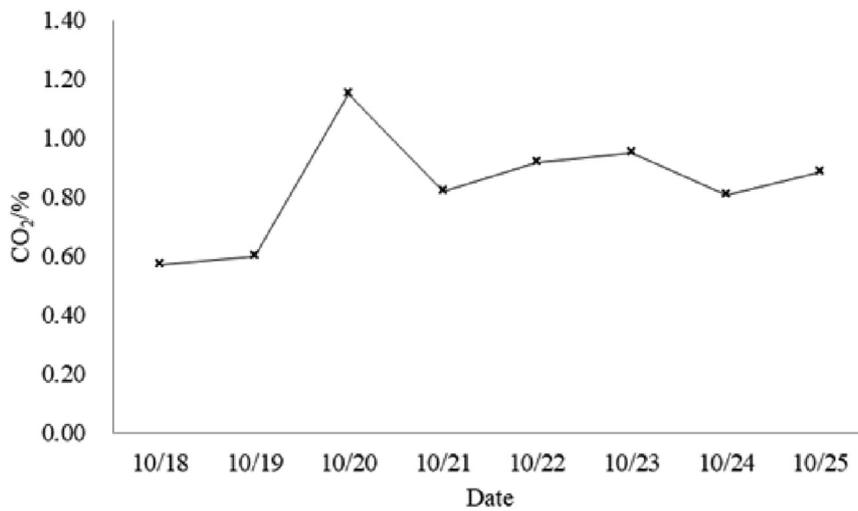

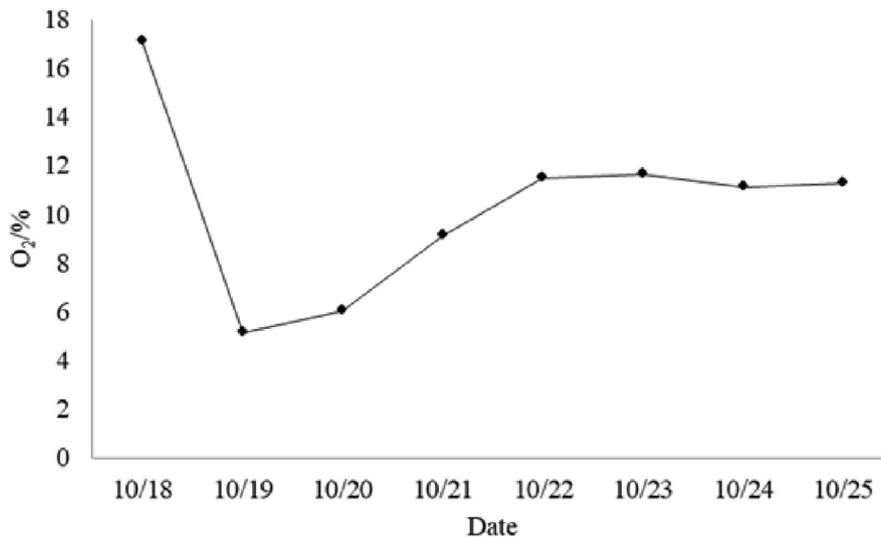**Fig. 8.** Curves of the CO_2 concentration at Point B.

Fig. 9. Curves of the O_2 concentration at Point A.

two. The concentration in the return airway in Test 2 and Test 6 exceeds the limit, so the evaluation result is zero. The volume of gas injection, depth of gas injection and air velocity at the working face are interrelated and mutually restrictive.

7. Example

On 17 October 2017, the No.7217 working face was about 90 m distance from the open cut hole in the Yaoqiao Coal Mine. Adopting the multisource injection techniques for use of carbon dioxide for fire prevention and extinguishing, the flow rate was about 540 m^3/h and the whole process consumed 24 h. Fig. 7 is a layout of the pipelines and monitoring locations.

The gas concentration was collected and measured at the depth of 60 m (Point A) and at the upper corner (Point B) on the goaf side of the return airway. The curves of the oxygen concentration at Point A and the carbon dioxide concentration at Point B are shown in Figs. 8 and 9.

The concentration of oxygen measured at Point A has an obvious downward trend after carbon dioxide injection. It falls to about 5%, and then rises to about 11%. The concentration of carbon dioxide at Point B barely changes, but shows a tendency to rise; the results are basically the same as the numerical simulation results. Therefore, the multisource injection technique for carbon dioxide can effectively reduce the width of the oxidised zone in a goaf.

8. Conclusions

(1) An index system of carbon dioxide injection for fire prevention and extinguishing was established by analysing the parameters of the gas injection pipe, mining technical conditions and physical qualities of the inert gas.

(2) Multisource injection techniques for use of carbon dioxide for fire prevention and extinguishing in goafs was put forward, and a mathematical multi-pipeline and multisource model was built on the basis of the diffusion model of carbon dioxide injection with a single pipeline.

(3) Based on an orthogonal test and fuzzy comprehensive optimisation theory, a parameter optimisation method was proposed to determine the process parameters of multisource injection techniques for carbon dioxide. By using the orthogonal test and FLUENT numerical simulation method, the relationship between injection parameters was studied. These included such as the mining speed at the working face, the gas injection position, the height of the pipeline outlet and the gas flow. Furthermore, the optimal injection parameters were calculated using fuzzy comprehensive optimisation theory with the results being gas injection volume 500 m^3/h, gas injection depth 90 m and pipeline number being two.

(4) The application of the model showed that the concentration of oxygen demonstrates an obvious downward trend after carbon dioxide injection when using the optimal parameters. This result is the same as from the numerical simulation. The multisource injection techniques for carbon dioxide could effectively reduce the width of the oxidation zone thereby preventing spontaneous combustion accidents in goafs.

Declarations

Author contribution statement

Junhong Si: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Genyin Cheng: Performed the experiments.

Jiangfang Zhu: Analyzed and interpreted the data.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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