Experiment and Analysis on Positive Pressure System of Mine Refuge Chamber

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Abstract
The positive pressure system of mine refuge chamber was evaluated in a simulation roadway, which was filled with three kinds of gas. The objective was to study the diffusion properties of CO, CH_4, and CO_2 and determine the target gases of positive pressure barrier in the refuge chamber. The mathematical model of the compressed O_2 supplying system is established. The harmfulness of CO was analyzed, through the test, CO was the most harmful gas because of its strong diffusivity and viscosity, it was difficult to exclude by ventilation when its concentration reached 10×10^{-6} ppm, lower concentration must be absorbed actively in the refuge chamber, because of its strong permeability, CO can penetrate 1m thickness wall by lateral diffusion. On this basis a 48-hour manned test with 8 miners in refuge chamber was conducted, the trapped participants can produce CO in rescue period, and the generation rate is 5.78 mg/h, the sensor of CO should be used infrared type. The conclusions from the research in the paper provide an important reference for the design of underground refuge chamber.
Keywords**:** SAFETY, VENTILATION, DIFFUSION PROPERTY, CO SENSOR, MANNED TEST

1. Introduction

According to statistics, only a small number of people died in the accident scene, about 90% of the people died of toxic and harmful gases in the mine fire and explosion accident [1], Refuge chamber can provide a safe and secure living environment for miners who cannot evacuate in time after the accident, Ounanian gathered evidence to conclude that the presence of mine shelters has had a potential positive effect on more than 32% of these events, with fatality rates reduction of over 29% [2]. The rescue of 33 Chilean miners trapped 700 m underground during 69 days has been considered the most successful rescue operation in mining history worldwide [3]. The importance of refuge chamber in underground operations has been highlighted.

The internal positive pressure of mine shelter plays the important role of isolating toxic and harmful gases. Oberholzer who is the scholar of South Africa proposed the refuge chamber must maintain a positive pressure to barrier the outside toxic and harmful gas [4]; MSHA rules that internal pressure of chamber must be higher 0.18 psi (1241Pa) than the external; The positive pressure control in general at 200~300Pa in other countries [5,6,7]. The specifications for coal mine mobile refuge chambers require as follow, the chamber should have enough airtightness and should always be higher 100 to 500Pa than the outside, it can be adjusted according to the actual situation. The pressure relief rate should not be greater than 350Pa/h at 500Pa [8].

The aim of this paper is to validate the positive pressure system of the mine refuge through the diffusion of three kinds of gas (CO, CH_4, and CO_2) inside the simulation roadway. By monitoring environmental parameters, the protective gas and pressure of refuge chamber was determined. The mathematical model of the compressed O_2 supplying system was established, and the rule of human metabolism CO was obtained. It is expected that the conclusions provide an important reference for the design of refuge chamber.

2. Material and Methods

2.1. Test Material

1) Simulation roadway

The experiments were performed in the closed simulation roadway. Fig. 1 shows the layout of testing roadway and equipment of inside the roadway. The tunneling place and inner wall of roadway were sealing treatment, and the wall thickness was 1 m, the width was 4m, the length was 15 m, the other end of roadway was plugging by the sealing wall, which the thickness was 1 m, the volume of the closed space was 192 m^3. The three measuring points are arranged in the roadway(as shown in Fig. 1), which the vertical height was 2.3m, 1.9m, 1.6m, each measuring point was placed with CO, CO_2, CH_4 sensor, the environmental parameter of roadway were uploaded to the monitoring room by the coal mine safety monitoring system which was KJ70 type.

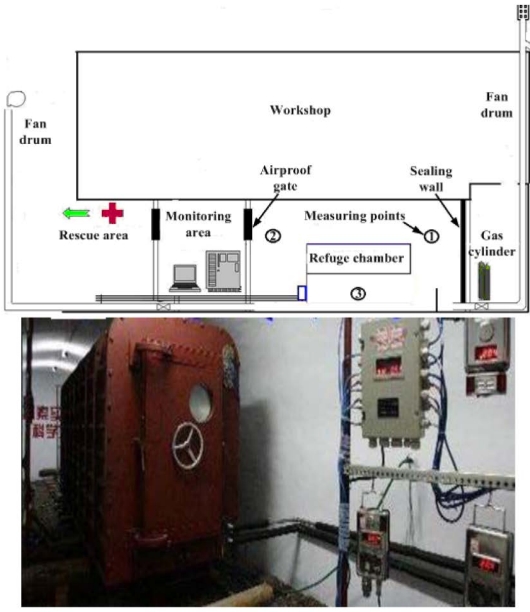


Figure 1. Layout of testing roadway and photograph of inside the roadway

2) Test chamber

The type of refuge chamber is double-layer steel structure with internal insulation materials which can effectively block the outside heat transfer and poisonous and harmful gas invasion. The air tightness of chamber is well, and the effective volume is 8m^3, the systems of refuge included the oxygen supply system, air purification system, temperature and humidity control system, monitoring system, communication system, and power supply system. The environmental monitoring system is CD7 type mining multi-parameter sensor, which can timely monitor environmental concentrations of CO, CO_2, CH_4, O_2, H_2S, temperature, and relative humidity inside the refuge.

2.2. Test Method

1) Gas diffusion test

In order to analyze the diffusion performances of CO, CH_4, and CO_2 in the roadway, and determine the main target gas that refuge chamber barrier by positive pressure system. The experiment was carried out in simulation roadway, which filling with toxic or harmful gases and simulating the disaster environment in the coal mine. The experiment procedure is as follow.

Open the monitoring instrument in the simulation roadway and close airtight door, then fill the roadway with the gases of CO, CO_2 and CH_4 in the same flow, record gas concentration of three measuring points, when the concentrations were balance, open fan to exhaust at the same wind speed, and record the concentration change of gases in three points.

2) Air tightness test

The aim of the test was to validate the air tightness of the refuge chamber. In order to prevent the poisonous and harmful gas from the roadway to the refuge chamber, the capsule must remain higher pressure than the outside. Table 1 shows the specification of military shelter about the cabin leakage, the test content was designed according to the specification and index.

Table 1. Test requirements of military chamber leakage

Chamber category	Pressure difference between inside and outside the chamber /Pa	Maximum air leak rate/ m^3•min^{-1}
Whole sealing, whole air conditioning, three-protection requirements	1470	0.05
Using air conditioning and forced draught	294	1.00
No air conditioning and closed chamber structure	294	6.00
No air conditioning and open chamber structure	98	6.00

The specific method depicts that the gas was sent to refuge chamber by the compressed air pipe, and adjust air throttle valve so that the pressure difference inside and outside the capsule reaches 1500 Pa, the time of positive pressure should not be less than 1 min; Check the extravehicular fasteners without soap bubble and splash phenomenon then record the data and calculate the amount of leakage of air per minute. The equation of the chamber leakage rate v is as follow

$$v = \frac{22.4V\Delta P}{1000RT\Delta t} \qquad (1)$$

where V is the volume of inside the chamber (8.6m^3), T is the temperature of inside the chamber, R is the universal gas constant, ΔP is the in time Δt, Δt is the time of pressure drop.

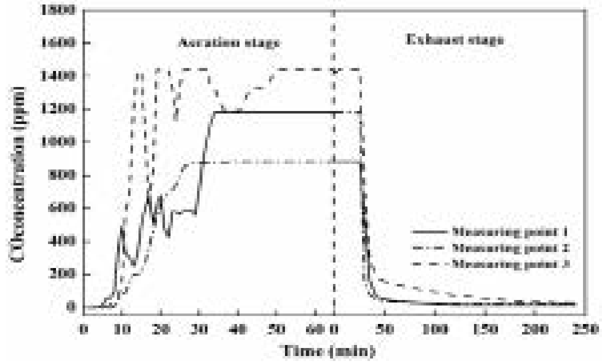
3) Barrier performance test

The test mainly studied the reliability of barrier performance of toxic and harmful gas. The chamber is closed during the test, open the air pressure system, and adjust the air intake and relief valve to control the pressure difference. In order to protect the operator, the pressure difference was at 200Pa~1000Pa [9]. CO, CO_2, and CH_4 were released to the roadway, their concentration respectively were 1000×10^{-6}ppm, 1%, and 1.5%. Record the environmental concentration of chamber and roadway, and analyze gas concentration of inside and outside the chamber to judge positive pressure barrier effect when the gas concentration in the roadway is stable about 3h.

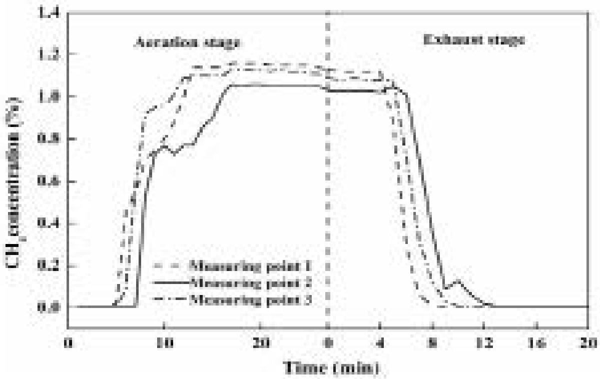
3. Results and Analysis

3.1. Analysis of Toxic and Harmful Gas Diffusion

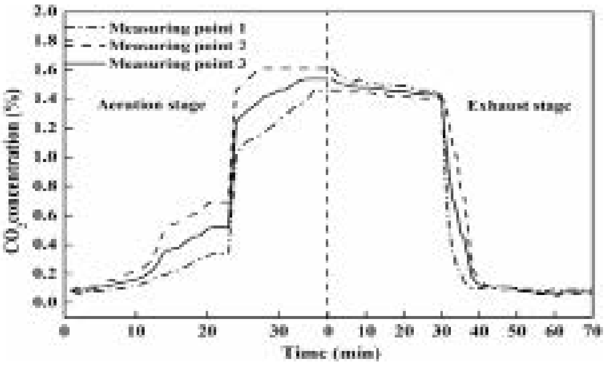
Fig. 2 shows that the diffusion situation of CO, CH_4, CO_2 in the simulation roadway during the filling and exhausting process. Three measuring points are respectively located inlet, outlet and the middle section of the roadway. CO concentration and different diffusion rates were great differences; it was mainly associated with the vertical height of the measuring point. Because the specific gravity of CO and air was 0.97, the height of position 3 accounts for 0.53 of the total height, it is the result that the diffusion rate of position 3 is the fastest. In addition, the stability of CO was poor; it has greater volatility and permeability in the diffusion process, after 11th minters, 1m thickness roadway was permeated, the concentrations in the monitoring area and workshop were 24ppm and 40ppm., CO concentration of workshop reached 100ppm in 20th minters, the highest level of monitoring area and workshop achieved 240ppm and 650ppm, the diffusion direction of CO



(a) CO



(b) CH_4



(c) CO_2

Figure 2. Toxic and harmful gas diffusion rule

presented transverse and longitudinal, its diffusion radius reaches nearly 100m; the diffusion trend of CH_4 and CO_2 are relatively stable and no great fluctuations. Through the calculation, the diffusion rates of the three gas under the same conditions in air are $v_{CO}>v_{CH4}>v_{CO2}$.

It is measured that concentration dilution rate of three gases at the same wind speed during the exhaust process (see Fig. 2) , the emission of CH_4 and CO_2 is relatively smooth and their exhaust times were short, the exhaust of CO appears different curves, the decreasing spread of higher concentration is rapid during the beginning of the exhaust process, when the concentration reduced 200×10^{-6}ppm, the speed slowed down, especially the concentration is at 24×10^{-6}ppm which is the safe limit concentration of human, its drop rate is very slow, when the concentration comes to 10×10^{-6}ppm, it is very difficult to remove by ventilation, the concentration almost does not decline, because of the fact that the density of CO is similar to that of the air, it shows higher intersolubility and viscosity during the exhaust process, part of the region exist CO concentration which still has the harm to the human body. Thus, the danger of CO in the accident is higher than the other two gases. As for the treatment of the low concentration CO in the confined space, the initiative way to absorb the gas is necessary.

3.2. Research on Pressure Model

1) Gas leakage rate

Fig. 3 depicts that pressure difference between inside and outside the chamber is decreased with time in the experiment of leakage rate. It is measured that the leakage rate significantly slow down with the pressure difference declining, According to the formula1, the leakage rate of refuge chamber is 0.00058m^3/min, which is far more than the military standard on the three-protection requirement of air leakage rate of 0.05 m^3 /min in closed chamber, so the refuge chamber gets good sealing performance.

1) Gas leakage rate

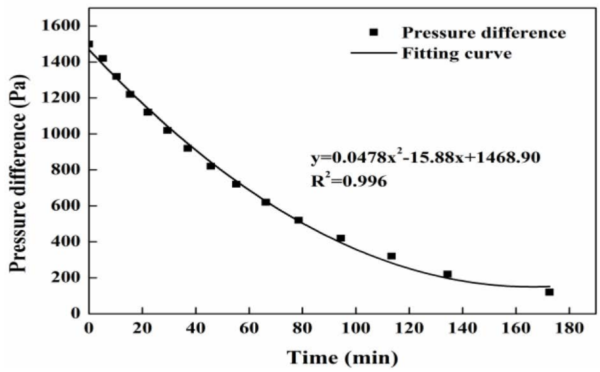


Figure 3. Relationship of gas leakage and time in positive pressure conditions

2) Chamber pressure model

During the rescue state, the gas pressure and the quality of the refuge chamber are affected by the following factors when oxygen was supplied by hyperbaric oxygen of chamber reserving, they included the O_2 consumption rate inside the chamber, the gas leakage, air supply and exhaust. Therefore, according to the quality change of gas and ideal gas isothermal equation, the formula is as follow:

$$d\Delta P = \frac{p_0 \times (Q_{in} - Q_{O_2} \times n - Q_{leakage} - Q_{out})dt}{V} \qquad (2)$$

where ΔP is the pressure difference inside and outside the chamber, P_0 is the standard atmosphere pressure, Q_{in} is the O_2 supplying rate, Q_{O2} is the O_2 consumption rate, $Q_{leakage}$ is the gas leakage rate, $Q_{out}$is the gas emission rate of pressure relief system, n is the number in the chamber; t-time, min; V is the volume of chamber.

In accordance with the relevant standards, the pressure difference of refuge chamber keep in the range of 200~1000Pa. Through calculation, oxygen supply system supplies 17L to the chamber in the initial state of no gas consumption. Make this a new starting point; the change of pressure inside the chamber should satisfy the relation shown in formula 2, and the pressure difference does not need to continue to rise, so the formula can be described simplify as follows

$$\frac{d\Delta P}{dt} = \frac{p_0 \times (Q_{in} - Q_{O_2} \times n - Q_{leakage} - Q_{out})}{V} = 0 \qquad (3)$$

During the rescue state, the mild activity time of trapped miners in the chamber was 90%, then moderate activity was 10%. Under these two conditions, the oxygen consumption rate was respectively 0.37L/min and 0.84L/min [10]. According to computation, Q_{O2} was 0.417L/min. According to the result of chamber gas leakage tests, the average leakage rate when the pressure decreased from 1000Pa to 200Pa $Q_{leakage}$ was 0.056V L/min

In a word, the relationships of oxygen system supply rate Q_{in}, pressure relief rate Q_{out}, chamber volume V and the number of hedging staff show as follows.

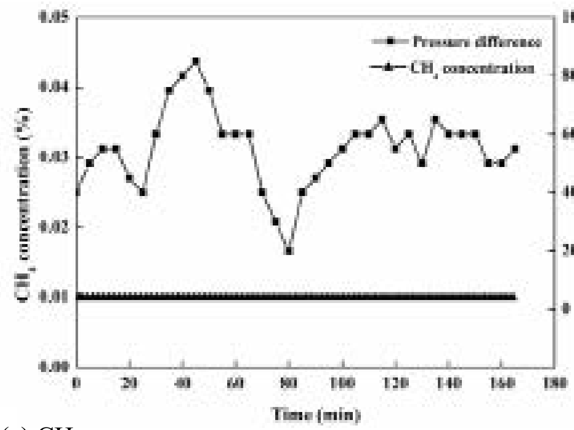
$$Q_{in} - Q_{out} = 0.417n + 0.056V \qquad (4)$$

3) Analysis of barrier performance

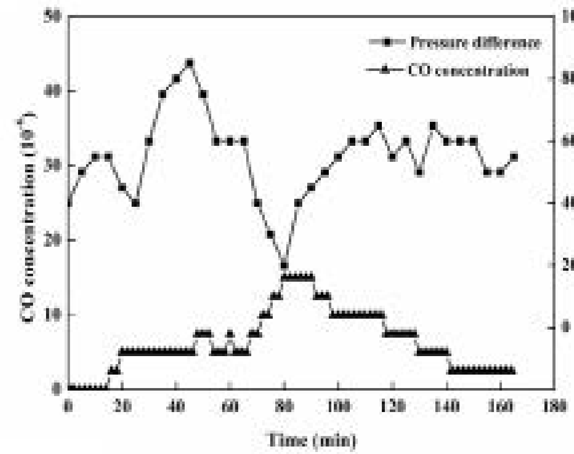
(1) Positive pressure barrier performance

Fig. 4 shows that the concentration of CH_4 and CO changed with the pressure difference. During the test, the refuge chamber always maintained positive pressure at 200~800Pa. By the environmental parameters of chamber, the CH_4 concentration is 0.01% in 3 hours, which is consistent with the initial data and without volatility. So the gas is not spread to the shelter and the pressure has a good barrier effect on CH_4. The effects of CO_2 is not considered in the test because of the testing personnel produced CO_2.

The concentration of CO was detected at the 16th minutes inside the chamber; it increased gradually with time and reached the maximum value of 15×10^{-6} ppm at the 80th minutes. It is measured that the concentration was related to pressure difference (see Fig. 4 (b)). When the pressure difference decreased, the concentration of CO increased corresponding. The pressure difference kept 500Pa, the concentration of CO is at 5×10^{-6}~10 ×10^{-6}ppm.

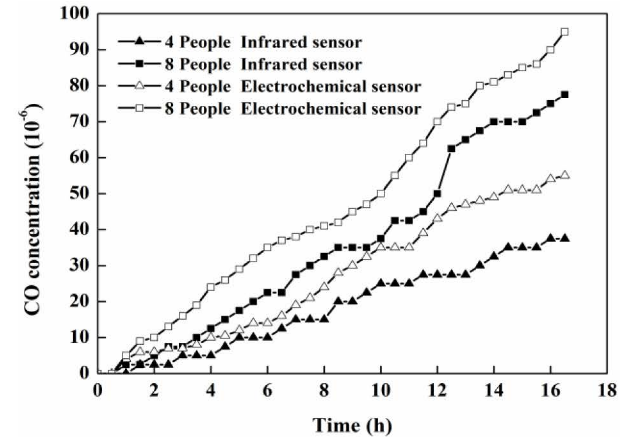


(a) CH_4

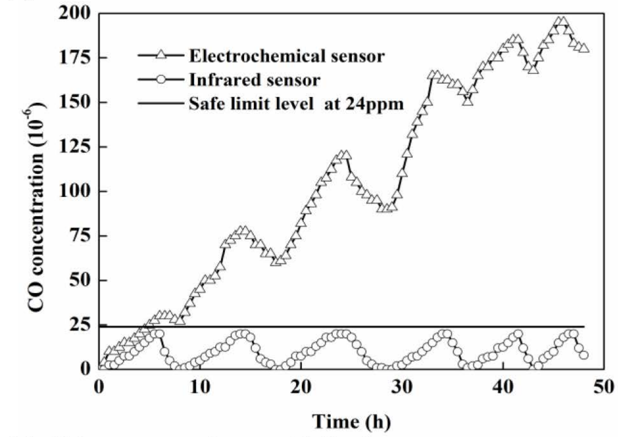


(b) CO

Figure 4. Positive pressure barrier performance



(a) Human metabolism CO



(b) 48-hour manned test with 8 miners

Figure 5. Environmental concentration of human metabolism CO

(2) Research of human metabolism CO

The positive pressure at 200~1000Pa inside the chamber can effectively barrier CH_4, but the CO concentration significantly increased. The source of CO may have two resources: the first is the external diffusion of CO into the cabin; the second is the generation of experiment staff. In order to make the further analysis of the source, the experimental research on human metabolism CO inside the chamber was conducted. Experiment was carried out in the simulation roadway, the toxic and harmful gases were absolutely exhausted. The experimental personnel were confined by life support system; the concentration of CO was monitored by infrared sensors and elec10trochemical sensor. There were 2 series of experiments, 4 and 8 about 25 years old healthy male experimental personnel entered the chamber. In order to determine the influence of sensor, the other experiments of 8 miners for 48h were carried out. Fig. 5 shows the result.

Compared with Fig. 4, CO concentration reached 5×10^{-6} ppm at 20^{th} minters and the time of the concentration of CO from 5×10^{-6} to 15×10^{-6} ppm was about 40min in the barrier performance test, then the concentration reached 5×10^{-6} at 200^{th} minters, it takes about 400min to improve the concentration of CO from 5×10^{-6} to 15×10^{-6} ppm. Therefore the source of CO in the chamber is mainly from the outside of the simulation roadway. When the concentration of CO outside of chamber was 1000×10^{-6} ppm, the concentration of CO was less than 10×10^{-6} ppm when the pressure difference was 500Pa. this can guarantee the safety of trapped miners.

According to the result of the test (Fig. 5 (a)), CO production rate were obtained (see Table 2). Through the calculation, the production rates of CO were 5.78 mg /h and 7.37 mg /h per person by infrared and electrochemical sensor, the detection value of two kinds of sensors were large gap, the value of infrared sensor are close to the results mentioned in Y.Z. She [11] test. To investigate the impact of sensors, a 48-hour manned test with 8 miners in refuge chamber was conducted During the 48 h of testing, in order to ensure the safety of personnel testing, when the concentration of CO was 20ppm, CO was removal by adsorbent. From the result of Fig. 5 (b), the error of electrochemical sensor was great, and then the result of infrared sensor can reflect the environmental pa-

Table 2. CO metabolism r ate

Groups	Electrochemical sensor			Infrared sensor		
	CO detection time(min)	Metabolism rate (mg/h)	Average metabolism rate (mg/h)	CO detection time (min)	Metabolism rate (mg/h)	Average metabolism rate(mg/h)
4 persons	58	7.21	7.37	89	5.68	5.78
8 persons	32	7.52		48	5.87	

rameters. The sensor of CO should be used infrared type in the refuge chamber.

4. Discussion

In the gas explosion and fire accidents of mine, many toxic and harmful gases spread in the roadway, which the main harmful gases conclude CH_4, CO and CO_2. J.S. Chen simulated the diffusion regularities of CO in roadway stope blasting [12]. The results showed that the diffusion rate CO fast, the removal of CO need to take long time, and the time is related to the wind speed. Z.C. Chen showed that it is difficult to completely eliminate CO by diffusion ventilation and the local ventilation equipment was installed [13]. So CO was the most harmful gas because of its strong diffusivity and viscosity. Some of the symptoms that may occur during prolonged exposure to carbon monoxide include dizziness, disorientation, nausea, and fatigue at concentrations less than 100 ppm [14].The increase of wind speed can reduce the CO concentration, but it is difficult to achieve in the refuge chamber. Because the higher speed ventilation increases noise and pressure of chamber and endanger the safe of haven person. So CO must be absorbed actively in the refuge chamber, the relevant standards of domestic and international are also described about removal rate and level of CO. The standard on refuge chamber of USA is lower than 25ppm (24ppm in China), and the max is 10ppm in the air quality of grade D compressed oxygen cylinders which MSHA required. The concentration decreased from 400ppm to25 ppm in 20min [5].

The positive pressure was controlled in general at 200~300Pa in many countries. MSHA rules that it is 0.18 psi (1241Pa) and the chamber should be higher 100 to 500Pa than the outside in China. The pressure difference is too low to block the effect by test, and too high to produce energy waste and be harmful to human body. H.R. Han considered that the pressure difference should be maintained above 100Pa by theoretical calculation when the air volume is 100L /min per person [15]. The refuge haven of Changcun Coal Mine N3 mining area designed that the minimum differential pressure was 100Pa [16]. The differential pressure of refuge chamber is related to air volume. F. You studied the air supply of refuge chamber from CO_2 dilution equation, heat balance, humidity equilibrium and O_2 balance. These studies only considered the dilution of the internal gas and ignored the infiltration of the external CO [9], no relevant tests were conducted to verify. The paper results show that the pressure difference in 500Pa can be controlled by CO in 10ppm. Therefore, this paper considers that the internal pressure difference of the rescue capsule should be controlled at 500~1000Pa. This has important implications for the revision of national standards.

Oxygen can be supplied to the miners when the refuge chamber worked. Many researchers only study the amount of oxygen in rescue [17], but the pressure will be changed by oxygen bottle, and the maintenance of positive pressure should be considered. They neglect this point. Through theoretical calculation, this paper established the relationships of oxygen system supply rate Q_{in}, pressure relief rate Q_{out}, chamber volume V and the number of hedging staff. It will be more conducive to the design and safety of the rescue capsule.

Human can produce CO during the rescue. J. LI study that the relevance ratio was 100% [18]. Y.Z. She study that the human body in the confined space can produce CO which is relevant smoke, age and environment, the production rate of CO is 5 to 6 mg /h [11]. It is similar to the research in this paper, and the production rate of CO is 5.78mg /h. There are no relevant regulations for monitoring method. During the period of hedge, the different sensors of CO may have an impact on environmental detection. The gas component is more complex in the human body in the confined space; the internal environment will have an impact on the sensitivity of the sensor. The electrochemical sensor detects gas concentration through reaction with the gas, the anti-interference ability is not strong, it will respond to some interfering gases[19], So due to the influence of environmental components, other gases will have interference with the monitoring system, leading to erroneous readings or false alarms. The experimental results electrochemical sensor has big error during the use of the rescue chamber. Therefore, the influence of CO detection device in the refuge chamber should be avoided. The research of this paper is important for the design and standard setting of refuge chamber.

5. Conclusions

In this paper, the following conclusions are drawn:

CO was the most harmful gas among the toxic and harmful gases after mine accident. Because of its strong viscosity, it is difficult to exclude by ventilation when its concentration reached 10×10^{-6}ppm, so low concentration CO must be absorbed actively in the refuge chamber. In addition, CO has a very strong permeability. It can penetrate 1m thickness wall by lateral diffusion. In order to prevent CO penetrating into refuge station, the wall should be treated with sealing material.

When the positive pressure is at 200Pa~1000Pa, the diffusion of CH_4 into refuge chamber can be controlled. The positive pressure is unable to separate CO completely because of its strong permeability. When the positive pressure reached 500Pa, the concentration of CO is safe for trapped miners. The mathematical model of the compressed O_2 supplying system is depicted as following: Q_{in}-Q_{out}=0.417n+0.056V.

Miners will produce CO in rescue period, and the detection rate is 100%. The production rates of CO is 5.78mg /h, the accumulation of CO will be harmful to human health with the increase of time, so the removing and monitoring device of CO must be set in the refuge chamber, the sensor of CO should be used infrared type.

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3-D tectonic stress field simulation for serious heterogeneous reservoirs

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Abstract
Turbidite reservoir with low permeability is an important reservoir type. Because of its complex structural feature and strong heterogeneity, there are some deficiencies in the three-dimensional tectonic stress field simulation. For instance, the geometry models and the structure of the reservoir do not fit well. Besides, the several mechanics parameters of the rock can't adequately reflect the reservoir heterogeneity. In this research, firstly the fine geological PETREL model is made in the way of faces-controlled modeling. It includes all the heterogeneity features of the turbidite reservoir, such as, fancies, lithology, and physical properties and so on. Then, the reverse engineering of cloud data is used to transfer the geological PETREL modeling into the mechanical ANSYS model. Thus the geological information is fully transfered into the ANSYS model. This greatly improve the accuracy of mechanical ANSYS model. Meanwhile, the rock mechanics parameters of the well is extended to the whole study area based on the three-dimensional velocity field PETREL model. This give the mechanical ANSYS model the properties of geology. What's more, the boundary conditions is determined referring to the stress of fractured well. In the end, the tectonic stress field simulation of the turbidite reservoirs with low permeability in FAN142 is carried out. According to the well measured stress, the accuracy of the simulation result is reliable and can find out the local abnormal tectonic stress caused by structural feature and heterogeneity of turbidite reservoir.
Keywords: THREE-DIMENSIONAL TECTONIC STRESS FIELD SIMULATION, TURBIDITE RESERVOIR, RESERVOIR WITH LOW PERMEABILITY, JOINT MODELING OF PETREL AND ANSYS, DONGYING DEPRESSION