Purification Characteristic Research of Carbon Dioxide in Mine Refuge Chamber

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Abstract

Refuge chamber is a kind of rescue equipment that protects trapped miners waiting for rescue in mine accidents. When a refuge chamber is in refuge state, carbon dioxide scrubbing is an important function of the environmental control system in chamber. In this paper, a series of experiments about the power consumption, purification efficiency, bed thickness and other factors of carbon dioxide scrubber in mine refuge chamber were carried out to obtain the optimal operating way. Then these parameters were testified by life supporting experiment in enclosed chamber.

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Keywords: Refuge chamber; Carbon dioxide; Air scrubber; Bed thickness; Purification characteristics

1. Introduction

Refuge chamber is a safety area provided for trapped miners when an accident occurs. It is able to prevent the explosive blast, high temperature fume, noxious gas outside and provide oxygen, carbon dioxide scrubbing, food and water for the trapped miners inside [1-3]. In the case of long-term survival in confined space, the uppermost gaseous pollutant is carbon dioxide generated by trapped miners [4,5]. Thus an air scrubber for refuge chamber was designed [6,7]. The main method of carbon dioxide purification domestic and international is to circulate the air inside chamber through the chemical agent, complete the removal of carbon dioxide and other toxic gases in the air. As to the refuge chamber in the United States, Australia and other countries, oxygen or liquid carbon dioxide cylinder are commonly used as power to drive air fan, achieving oxygen supplying or refrigerating while air purification process [8]. But activating
air fan requires large amounts of compressed gas; accordingly, this method is generally applicable to the refuge chamber of larger volume or oxygen requirement. Due to the complexity of coal mine conditions in China, the external dimensions of the refuge chambers are relatively small; battery is the main power storage device for the explosion-proof electric fan.

Because of the space limitation of the refuge chamber in our country and some special cases, such as power outages or high-temperature that might occur in refuge state, the absorption performance of the air scrubber can be influenced by energy, agent consumption, the convenience of changing agent, agent storage, absorption stability, staff operational level and other factors [9]. In order to determine whether it could achieve low-power and high-efficiency removal of carbon dioxide in refuge state, the performance of air scrubber under different conditions were studied as follows.

2. Experimental environment and method

2.1. Agent performances

The agent named JS-1, developed by our research group was used in experiment as carbon dioxide absorbent. JS-1 was an white, granular solid, with loose and porous structure. Its particle size was in the range of 2-6mm, stacking density was 0.5 g/mL. It can absorb acid gases, such as carbon dioxide, sulphur dioxide. Indicator was added in JS-1 during production, thus it appears pink. As absorb carbon dioxide, it will turn to white or faint yellow, which indicates that the agent bed should be changed. The carbon dioxide absorption efficiency is around 21%, slightly more than the average carbon dioxide absorption agent, but has the virtues of low cost, convenient operation and mature technology.

2.2. Experimental environment

1) Experimental environment

The experiments were carried out in the sample chamber. Its inner space size was 4200mm × 1200mm × 1700mm, and the total volume is 8.6m³. Square model steels were used as braced frames of the capsule. The structure of sample chamber was sheet metal. The bulkhead was double steel structure, both internal and external steel plates were 1.2mm thickness low-carbon steel plate, filled with 5cm thickness thermal insulation materials. The side face of the sample chamber is equipped with an observation window.

2) Experimental equipment

The main equipments used in the experiment included: Rock E40 series PLC data acquisition, a variety of GTY1000 25 carbon monoxide, oxygen combined sensor, KGF2 wind KGY7-type pressure sensor, KGW5 digital temperature sensor, F200 IAQ-CO₂ monitoring and multi-function controller.

2.3. Experimental method

The absorption performance of the air scrubber was tested in the sample chamber under different power and bed thickness conditions, thus the optimal operating condition, energy consumption, life cycle, bed thickness and other performance parameters were determined. Then the living simulating experiment was carried out to verify the performance of the air scrubber.
3. Results and discussions

3.1. Performance of air scrubber under different power conditions

(1) Performance of air scrubber under different power conditions

To test the relations between absorption rate and power of air scrubber, experiments (1) was designed as follows:

Adjust air scrubber, and purification experiments were carried out with the air scrubber power under 8 operation states: 5W, 10W, 20W, 30W, 50W, 70W, 90W, 120W. In the sample chamber, the initial concentration of carbon dioxide was 30000 ppm or so, and the change of carbon dioxide concentration was recorded under the conditions of different power. Carbon dioxide absorption under different power see figure 1.

![Fig.1 The decreasing time of CO2 concentration at different powers](image)

As shown in Fig 1, carbon dioxide concentration in the confined space dropped quickly from 3.3% to 0.5% under the action of air scrubber, and carbon dioxide absorptive amount was 240L. Carbon dioxide absorption rate is proportional to the input power of the fan, and the absorption time is inversely proportional to the power. When the fan power was 90W, carbon dioxide was absorbed completely in 7 minutes, which showed that in the range, the greater the fan power was, the more air went through the scrubber in each unit time. That was because the reaction between carbon dioxide and potions bed was run fully, then the absorptive rate was higher.

When the fan input power further increased, the absorption rate gradually decreased. When the input power was 120W, the absorption rate was equalled to that of the power was 50W. During this process, the power increase made the airspeed exceeded high, and there was not enough reaction time of the carbon dioxide and the agents bed. It was showed that the air flow rate was also a very important parameter. When the airspeed was too high, even with improvement of the ventilation, it could not increase the absorptive efficiency. Thus, when flow reached a certain level, in order to further increase the absorptive rate, increasing the thickness or surface area of agents bed to reduce airspeed was well considered.

(2) The optimal running power of the air scrubber

To improve the absorptive efficiency, reduce energy consumption and noise pollution, selecting the appropriate airspeed became an important condition. Through the absorptive tests of carbon dioxide under different power, the optimal running power of the air scrubber was determined under the different needs of absorption. Through experiment (1) the relation curve of the decreasing time of carbon dioxide and the power consumption was obtained, which was shown in Fig 2.
As shown in the Fig 2, when the fan power was 100W, the absorptive efficiency was the highest. At this time, the maximum airspeed of the absorptive bed could be calculated according to equation 1.

\[ GHSV = \frac{Q}{V} \]  

(1)

Where:

- \( GHSV \) = airspeed (h\(^{-1}\));
- \( Q \) = air flow (m\(^3\)/h);
- \( V \) = volume of the absorptive bed (m\(^3\)).

The air flow through the air scrubber was 667m\(^3\)/h, therefore the maximum airspeed of the absorptive bed was 13333h\(^{-1}\).

As shown in the Figure 2, when the weights of the absorptive time and power consumption were equal, 10W was the best absorptive power; In exceptional cases, carbon dioxide concentrate raised too fast, the air scrubber could be run at 10W, when air flow was 90m\(^3\)/h, and the airspeed of the absorptive bed was 1800h\(^{-1}\). In practical aid state, in order to ensure longer air purification time, power is the primary performance indicators. In the condition of carbon dioxide concentration was less than 1% in the chamber, the selection criteria was the lowest energy consumption, the Figure 1 shown that by the air scrubber running at 5W was the best energy consumption point. While 8 persons were accommodated in the refuge chamber as the standard load state, according to the body’s normal metabolic respiration, each person produced 0.4L/min of carbon dioxide, and the carbon dioxide production rate in the chamber was 3.2L/min. While the absorptive rate of the air scrubber running at 5W is 13L/min, which fully met absorptive needs for 8 persons in the confined space. At this time, air flow was 45m\(^3\)/h, and the airspeed of the absorptive bed was 900h\(^{-1}\).

Fitted curve with polynomial approximation tools of matlab \(^{[10,11]}\), the thickness of the absorptive bed (20kg) was determinated, the function between carbon dioxide absorptive time and the power was:

\[ y = 6.42 \times 10^{-7} x^4 - 1.79 \times 10^{-4} x^3 + 0.018 x^2 - 0.8 x + 21.41 \]  

(2)

Fitting function correlation coefficient R-square: 0.983, residual sum of squares SSE: 1.89, confidence level of the function: 95%.
3.2. Performance of air scrubber under different bed thickness conditions

In order to obtain performance ratio between the thickness of the absorptive bed and absorptive time, experiment (2) was designed as follows:

Air scrubber was placed with 1kg, 2.5kg, 5kg, 8kg, 20kg JS-1 agents, and run at 5W. Relation curve of the decreasing time of carbon dioxide and the bed thickness was shown in Figure 3.

As was shown in Fig 3, when the thickness of agent bed was too thin, carbon dioxide and agent contacting time was too short; and excessive increase in bed thickness would increase air resistance and take up more volume. Moreover it could be known from the figure, with the dosage increased, the absorptive time decreased trend gradually slowed down. The specific relation between bed thickness and absorption time was shown in Fig 4.

As was shown in Fig 4, the best relative point of the bed thickness and absorptive time was the point which was nearest point from the origin, then the absorptive bed thickness was 8kg, and packing density was 16L, within the permissible range of the volume in the confined space, and according to theoretical calculations, it could absorb 800L carbon dioxide, which was breathing exhalation amount of 8 persons in 220 minutes in the normal state. Because the activity was relatively reduced in a closed chamber, the
amount of exhaled carbon dioxide was also reduced, which meant it meets carbon dioxide removal needs for about 8 persons in 6 hours, so 8kg agent was chosen in the air scrubber.

3.3. Analysis of absorbent bed life cycle

In the theoretical case, every 8 persons would use 20kg absorptive bed in 10 hours, but due to equipment limitations, the actual reaction might not reach the extent of laboratory tests. When the effective absorbent ingredient of the absorption bed content was relatively low, the ability to control carbon dioxide might drop, so it was very necessary important to explore the real life of each absorptive bed.

New absorptive bed was placed in the air scrubber, and the loading capacity is 20kg. The 4 persons’ amount of normal respiratory metabolism was simulated, with the carbon dioxide rate of 1.6L/min flowing into the chamber. At the same time open the air scrubber run at 5W, theoretically, it could maintain the carbon dioxide concentration for 4 persons in 20 hours. Fig 5 shown the change in carbon dioxide concentration in the chamber.

![Fig.5  CO₂ absorption effect of using 20Kg chemical](image)

As shown in the Fig 5, during the 800 minutes, carbon dioxide concentration remained at the range of 0.1%, the carbon dioxide concentration in the chamber had no significant fluctuations, and the absorptive agent was fine; during 800-1000 minutes, the carbon dioxide concentration started to rise, but the speed was relatively slow, and it was still in the safe limits; 1000 minutes later, the carbon dioxide concentration began to rise quickly, and after 1150 minutes, the carbon dioxide concentration was close to 0.5%, the effect of air scrubber became weaken obviously, so the new bed must be replaced at this time. To ensure safety, the absorption bed should be changed within 1100min (18.4h). Therefore, in case of 8 people, the service life of each absorption bed was 9.2h. If using the standard absorption bed according to the design demands, the service life can be to 3.7h.

3.4. Living simulating experiment

The basic experiments above determined power consumption, purification efficiency, bed thickness and other basic parameters of air scrubber in mine refuge chamber. But the experimental conditions were based on simulated respiratory states. In the real rescue process, respiration changes greatly under different states of human activities, in addition, temperature and humidity also have a great impact. These
parameters will relevantly influence the absorption performance of air scrubber, thus it is necessary to verify the performance of air scrubber through living simulating experiment.

Four healthy male volunteers were randomly selected for the living simulating experiment. Put 5.5kg JS-1 agent in the air scrubber, fan power was 5W. The variation of carbon dioxide during the experiment was showed in Fig 6.

![Fig.6 CO2 concentration in life supporting experiment](image)

As shown in Fig 6, 5.5kg JS-1 agent can maintain 504min (8.4h) suitable living of four volunteers, what means that the service time of 8kg JS-1 agent for 8 healthy male is 367min. Table 1 showed carbon dioxide absorption rate.

**Table 1 The absorption data of carbon dioxide in life supporting experiment**

| Time/min | Variation of concentration % | variation quantity of concentration/% | Total Time /min | Carbon dioxide respiratory rate or absorption rate/L•min⁻¹ |
|----------|-----------------------------|--------------------------------------|----------------|----------------------------------------------------------|
| 8-43     | 0.82-0.32                   | 0.50                                 | 35             | 1.14(absorption rate)                                     |
| 43-68    | 0.32-0.75                   | 0.43                                 | 25             | 0.34                                                     |
| 68-128   | 0.75-0.45                   | 0.30                                 | 60             | 0.4(absorption rate)                                     |
| 128-163  | 0.45-0.78                   | 0.33                                 | 35             | 0.19                                                     |
| 163-181  | 0.78-0.30                   | 0.48                                 | 18             | 2.13(absorption rate)                                   |
| 181-236  | 0.30-0.79                   | 0.49                                 | 55             | 0.18                                                     |
| 236-255  | 0.79-0.31                   | 0.48                                 | 19             | 2.02(absorption rate)                                   |
| 255-313  | 0.31-0.79                   | 0.48                                 | 58             | 0.17                                                     |
| 312.340  | 0.79-0.32                   | 0.47                                 | 27             | 1.39(absorption rate)                                   |
| 340-388  | 0.32-0.79                   | 0.47                                 | 48             | 0.2                                                      |
| 388-420  | 0.79-0.30                   | 0.49                                 | 32             | 1.23(absorption rate)                                   |
| 420-466  | 0.30-0.81                   | 0.51                                 | 46             | 0.22                                                     |
| 466-495  | 0.81-0.41                   | 0.40                                 | 29             | 1.1(absorption rate)                                    |
| Average  |                            |                                      |                | 0.22(respiration)                                        |
|          |                            |                                      |                | 1.34(absorption rate)                                   |

From Table 1: during the living simulating experiment, the absorption rate of JS-1 agent was relatively stable. It generally took 30min to absorb 40L carbon dioxide. The average absorption rate was around
During 40% of the test time the air scrubber was in working condition, the whole energy consumption was 18Wh.

4. Conclusions

Through experiments, related important parameters of the air scrubber and IS-1 agent were determined. Based on this, the optimal operational performance and using mode of the air scrubber using in a confined space were presented. It is of great importance to provide a guide for the designing and improving existing air scrubber. The concrete conclusions are as follows:

1) Optimum reaction conditions of remove carbon dioxide in the refuge chamber: dose of JS-1 agent is 20kg, optimal operating power is 100W;
2) The minimum operating power of the air scrubber to fit rescue requirements is 5W, while 10W in emergency state.
3) Due to the limitation of energy storage in the refuge chamber, the air scrubber is suggested operating at intermittent mode, the optimal proportion of running time and down time is 2:3. When operating at intermittent mode, the air scrubber will consume only 27% energy of that at continuous operating mode to achieve the same absorption rate conditions.
4) The optimal dosage of JS-1 agent for 8 people is around 8kg. When the respiration is 0.4 L/min, it can maintain 3.7 hours.
5) In the living simulating experiment, the service life of 8kg JS-1 agent for 8 people can reach 6.1 hours, the average absorption rate is 1.34L/min.

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