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Theoretical and numerical simulation of critical gas supply of refuge chamber

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ABSTRACT

The personnel in refuge chamber absorb O_2 and exhale CO_2 all the time. Supplying O_2 and removing CO_2 are the basic function of refuge chamber. After disaster occurs, the supply of the compressed air or oxygen for personnel in refuge chamber is limited. Thus, how to effectively use the compressed air and oxygen and try to improve the time of supply has a great significance. Supplying more oxygen will result in waste, while supplying less oxygen will cause its concentration to be lower, and harm life safety. This research uses the theoretical calculation and numerical simulation, finds critical gas supply for refuge chamber, and illuminates the change law of gas concentration with critical gas supply in refuge chamber, which provides theoretical guidance for effective use of compressed air and oxygen in refuge chamber.

1. Introduction

Refuge chamber is an important constituent part of six systems for safety coal mine, provides survival guarantee for personnel in coal mine in a long time, and tries best to reduce the injuries and deaths caused by accidents [1]. As the construction and application of refuge chamber speed up, more problems appear in the course of application, which urges to research the refuge chamber in depth. The supply of oxygen in refuge chamber is the first and foremost condition that guarantees the personnel to be safe, and it can be divided into compressed air and compressed oxygen. Previous studies have focused on the supply of oxygen. Gao et al. studied the calculation method of two ways of supplying oxygen (compressed air and compressed oxygen) [2]. Xiong contrastively analyzed the advantages and disadvantages of supplying oxygen by compressed oxygen, superoxide and oxygen candle, and proposed an optimized scheme of self-provided supply of oxygen in refuge chamber [3]. Jin et al. investigated the theoretical calculation method for different ways of oxygen supply, and characteristics of supplying oxygen in laboratory [4]. Zhang et al. researched on characteristics and law of supplying compressed oxygen in use of 50 persons for testing in refuge chamber [5].

Besides, Sun focused on the site selection, control of environment temperature, monitor and control, personnel escape, etc. [6]. Yu et al. discussed the internally environmental quality requirement in refuge chamber based on the related regulations of *State Administration of Coal Mine Safety* [7].

From studies mentioned above, it is clear that the technologies in refuge chamber have made great progress, especially focused on sufficient supply of oxygen and removal of toxic and harmful gas. Atmospheric environment in refuge chamber is in dynamic equilibrium from beginning to end, and air exchanges with external atmosphere. In other words, the waste gas is discharged from refuge chamber when the compressed air or oxygen is input into refuge chamber. It is certain that the discharged waste gas includes oxygen, which caused the waste of oxygen indirectly. With the condition of limited compressed air or oxygen, it is great significant to use oxygen effectively, prolong the time of supplying oxygen, and reduce the discharge of unnecessary oxygen. This study used the theoretical and numerical simulation, and investigated the minimum of critical supply of oxygen in refuge chamber, which can guarantee the minimal oxygen in discharge and try to prolong the time of oxygen supply.

2. Geometric model of refuge chamber

According to the practical conditions of refuge chamber, the geometric model was established, with 3.8 m long and 2 m × 2 m cross section (Fig. 1). Test of five persons' survival was simulated. The model includes the inlet and outlet of air or oxygen, air cleaner, seats, and fan producing air circulation.

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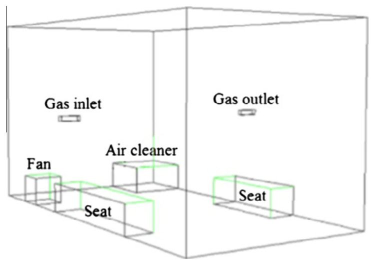

Fig. 1. Geometric model of refuge chamber.

3. Theoretical analysis of critical gas supply in refuge chamber

After the accidents occur, the pipeline will continue supplying oxygen (air or pure oxygen). No-stop inputting oxygen (air or pure oxygen) into refuge chamber will make the refuge chamber produce positive pressure. Until that the pressure in refuge chamber exceed external pressure 300 MPa, pressure relief device begins to discharge pressure. When the difference of the internal pressure in refuge chamber and external pressure in atmosphere reaches 100 Pa, the discharge will stop, which goes and returns in a circle.

3.1. Mathematical model of gas supply for refuge chamber

According to geometric model of refuge chamber (Fig. 1), the air supply model of refuge chamber was established (Fig. 2). As shown in Fig. 2, Q_I is the input airflow, L/min; Q_O is the discharge airflow, L/min; C_{ICO2} is the volume fraction of CO_2 at the inlet,%; C_{OCO2} is the volume fraction of CO_2 at the outlet,%; C_{IO2} is the volume fraction of O_2 at the inlet,%; C_{OO2} is the volume fraction of O_2 at the outlet,%; U_{CO2} is the rate of CO_2 generating in refuge chamber, mainly the rate of CO_2 generating by personnel in refuge chamber, L/min; U_{O2} is the rate of consuming O_2 in refuge chamber, L/min; and V is the volume of the whole refuge chamber, m^3.

Assuming that the difference of pressure in refuge chamber and pressure in atmosphere keeps at 100 pa all the times and temperature maintains constant, Q_I is equal to Q_O, without considering the influence of moisture. Assuming that gas input into refuge chamber can be mixed evenly and concentration of gas in everywhere of refuge chamber is equal, the volume fraction of CO_2 at the outlet is equal to that in the whole refuge chamber, and the volume fraction of O_2 at the outlet is equal to that in the whole refuge chamber.

3.1.1. Mathematical model of CO_2 concentration dynamic change in refuge chamber

Within a period of time t, three aspects cause the volume fraction of CO_2 to change: the first one is CO_2 in the gas supplying for refuge chamber; the second one is CO_2 exhaled by persons in refuge chamber; the third one is that the outlet will take some CO_2 away. The differential relation of C_{OCO2}, C_{ICO2} and t meets following equation [8].

$$VdC_{OCO2} = Q_I C_{ICO2} dt + U_{CO2} dt - Q_O C_{OCO2} dt \tag{1}$$

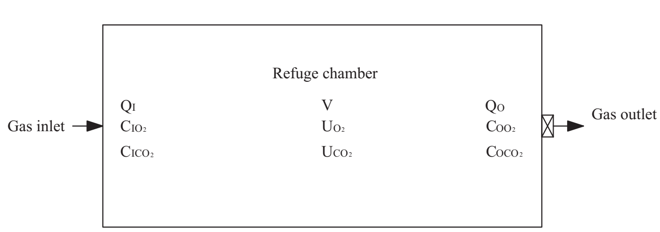

Fig. 2. Model of gas supply in refuge chamber.

where $Q_I = Q_O$, let be $Q = Q_I = Q_O$, m^3/s; t the duration of gas supply, s; dt the random period of time during air supply; dC_{OCO2} the change of CO_2 volume fraction within dt in refuge chamber. Eq. (1) is changed as follows [8]:

$$\frac{dC_{OCO2}}{dt} = -\frac{Q}{V} C_{OCO2} + \frac{QC_{ICO2} + U_{CO2}}{V} \tag{2}$$

Solving Eq. (2) gets Eq. (3) as follows:

$$C_{OCO2} = X_0 \exp\left(-\frac{Qt}{V}\right) + \left(\frac{U_{CO2}}{Q} + C_{ICO2}\right)\left[1 - \exp\left(-\frac{Qt}{V}\right)\right] \tag{3}$$

where X_0 is the initial volume fraction of CO_2 in refuge chamber, %.

3.1.2. Mathematical model of O_2 concentration dynamic change in refuge chamber

Within a period of time t, three aspects cause the volume fraction of O_2 to change: the first one is O_2 in the gas supplying for refuge chamber; the second one is O_2 absorbed by persons in refuge chamber; the third one is that the outlet will take some O_2 away. The differential relation of C_{OO2}, C_{IO2} and t meets following equation.

$$VdC_{OO2} = Q_I C_{IO2} dt - U_{O2} dt - Q_O C_{OO2} dt \tag{4}$$

Solving Eq. (4) and get Eq. (5) as follows:

$$C_{OO2} = Y_0 \exp\left(-\frac{Qt}{V}\right) + \left(C_{IO2} - \frac{U_{O2}}{Q}\right)\left[1 - \exp\left(-\frac{Qt}{V}\right)\right] \tag{5}$$

where Y_0 is the initial volume fraction of O_2 in refuge chamber, %.

3.2. Concentration distribution of CO_2 and O_2 in refuge chamber with the condition of air supply

3.2.1. Concentration distribution of CO_2 and O_2 in refuge chamber with the rated air supply

According to *Temporary Provisions on the Construction and Management of the Coal Mine Underground Emergency Refuge System* (hereinafter referred to as *Temporary Provisions*), air supply should not be lower than 300 L/min per person. When the air supply is 300 L/min per person, the total air supply for five persons is Q = 1500 L/min. CO_2 concentration in the air is C_{ICO2} = 0.05%, while O_2 concentration in the air is C_{IO2} = 21%. The rate of CO_2 exhaled by a person is 0.41 L/min, total U_{CO2} = 2.05 L/min for five persons. The rate of O_2 consumed by a person is 0.33 L/min, total U_{O2} = 1.65 L/min for five persons. Under the condition of air supply, CO_2 volume fraction in refuge chamber at initial time is equal to that in the air, that is, $X_0 = C_{ICO2}$ = 0.05%; O_2 volume fraction in refuge chamber at initial time is equal to that in the air, namely, $Y_0 = C_{IO2}$ = 21%. The volume of refuge chamber is 15.2 m^3. Substituting the above values into Eqs. (3) and (5) can get concentration distribution of CO_2 and O_2 in refuge chamber under the condition of rated air supply, as shown in Fig. 3.

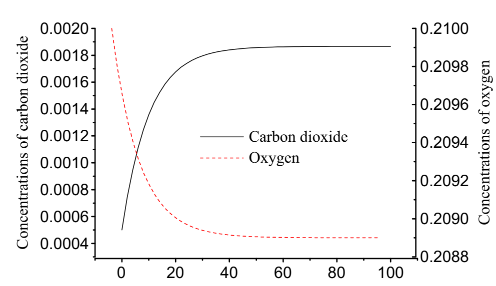

Fig. 3. Dynamic distribution of CO_2 and O_2 concentrations with rated air supply.