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Research on Low-Oxygen Air Displacement Technology for Gas Drainage Boreholes

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Abstract: This paper addresses the issues of low efficiency and high safety risks in coal seam gas extraction by proposing a gas extraction technology based on low-oxygen air displacement. Oxygen content below 8% was prepared by membrane separation, pressure swing adsorption, and oxygen-absorbing and oxygen-releasing agent technology. The ratio of oxygen-absorbing and oxygen-releasing agents was optimized through orthogonal experiments, and the effects of cobalt oxide (CoO), ferrous oxide (FeO), and additives on oxygen consumption were analyzed. The research shows that cobalt oxide contributes the most to the oxygen reduction effect, and the optimal material ratio is cobalt oxide: ferrous oxide: additive = 4:2:1, which can significantly reduce the oxygen content of the injected gas and achieve recycling. The low-oxygen air displacement technology enhances the desorption efficiency of methane through gas displacement, eliminates the risk of gas explosion, and reduces equipment corrosion. This technology provides a new method for the safe and efficient extraction of gas from low-permeability coal seams, with both engineering practicality and environmental safety.

Keywords: Low-oxygen Air Displacement; Gas; Oxygen-absorbing and Oxygen-releasing Agent; Orthogonal Test.

1. Introduction

The research and application of gas displacement technology for methane in gas drainage boreholes have received significant attention in the field of coalbed methane management in recent years, especially in enhancing methane extraction efficiency and reducing the risk of coal mine gas disasters. This technology involves injecting gases (such as carbon dioxide CO_2, nitrogen N_2 or steam) into the boreholes to displace methane in the coal seam, based on the differences in adsorption and fluid dynamics characteristics among gases, to improve the effectiveness of gas drainage.

Gas displacement technology for coalbed methane (CBM) involves injecting specific gases into CBM extraction boreholes to alter the gas composition and pressure distribution within the coal seam, thereby promoting the desorption and flow of methane. This method is similar to enhanced oil recovery (EOR) techniques in the petroleum industry but has been adapted to the unique characteristics of CBM extraction. For instance, carbon dioxide (CO_2) is effective in displacing methane from coal due to its stronger adsorption capacity compared to methane (studies show that the adsorption capacity of CO_2 is approximately twice that of methane) [1]. Nitrogen, with its lower adsorption capacity, is suitable for flushing methane, especially in coal seams with high CO_2 content.

This technology is mainly applied in the extraction of coalbed methane underground, especially in low-permeability coal seams where the efficiency of conventional extraction is relatively low. For instance, in coal mines in Australia and China, gas displacement technology is used for pre-extraction to reduce the methane content in coal seams, lower the risk of methane explosions and outbursts, and also provide the possibility for the utilization of methane resources [2]. Additionally, this technology is combined with carbon capture and storage (CCUS) to achieve emission reduction goals, such as promoting methane extraction and CO_2 storage simultaneously through CO_2 injection [3].

Studies have shown that CO_2 injection can significantly enhance the recovery rate of methane. For instance, Reznik et al. [4] experimentally demonstrated that CO_2 injection can increase the methane recovery rate by 2 to 3 times, especially under high-pressure conditions. Numerical simulations and laboratory experiments (such as models based on Fick's law and the Langmuir isotherm equation) are widely used to investigate the impact of CO_2 injection on coal matrix deformation and gas flow. Recent studies have also explored the influence of injection pressure on efficiency and safety, indicating that higher pressure can shorten the extraction time but may reduce the efficiency of carbon sequestration [5]. Nitrogen, due to its lower adsorption capacity, is used to enhance gas drainage, particularly in coal seams with high CO_2 content. Laboratory studies (such as six-cycle nitrogen injection experiments) have shown that nitrogen flushing can improve drainage performance, especially in low-permeability coal seams [6]. However, field tests are scarce, and research is still in its early stages, with ongoing debates regarding the long-term stability of coal seams under nitrogen injection. Steam injection has also been proposed as a potential method to enhance methane desorption through thermal effects, but research is limited, and there is a risk that injected water may clog gas channels [7]. Additionally, recent studies have explored high-pressure multi-discharge CO_2 gas fracturing technology to increase the permeability of thick coal seams and thereby enhance gas drainage efficiency [8]. Laboratory experiments mainly include adsorption experiments and fluid-solid coupling model simulations to study the impact of gas injection on coal seam permeability and gas desorption. Field tests have been conducted in coal mines in Australia and China, such as enhanced recovery field tests with nitrogen injection, which have verified its feasibility under actual conditions [2]. However, the scale of these tests is limited, and the data are insufficient to comprehensively evaluate the long-term effects.

The current research status of gas displacement technology for methane extraction in gas drainage boreholes shows that

it significantly enhances the efficiency of methane extraction through the injection of CO_2 and nitrogen, especially in low-permeability coal seams. Although both laboratory and field tests have provided positive results, large-scale application still needs to overcome geological complexity and economic challenges. In the future, through technological optimization and multidisciplinary integration, this technology is expected to further improve the efficiency and safety of methane management in coal mines.

The low-oxygen air gas displacement technology for methane involves injecting air with a low oxygen content (typically rich in nitrogen) into methane extraction boreholes to promote the desorption and flow of methane in coal seams. Unlike traditional gas displacement techniques that use pure nitrogen or carbon dioxide (CO_2), the low-oxygen air method takes advantage of the properties of nitrogen, the main component of air, by reducing the oxygen content to lower safety risks while achieving methane displacement. The oxygen content in standard air is approximately 21%, while low-oxygen air can reduce this to 5% or less, similar to nitrogen-enriched air.

The background of this technology stems from the practical need for coalbed methane extraction. Coalbed methane (mainly methane) is one of the major safety hazards in coal mines and also an important energy resource. Traditional methods such as nitrogen injection are suitable for coal seams with high CO_2 content due to their relatively low adsorption capacity, while CO_2 injection can effectively displace methane due to its strong adsorption capacity on coal [4]. The low-oxygen air technology attempts to strike a balance between cost and effect, especially in coal mines with limited resources.

Most of the research on air displacement of coalbed methane is qualitative textual description, lacking systematic and quantitative physical explanations. Against the backdrop of large-scale development of coalbed methane, relevant research is urgently needed to be addressed. Therefore, it is of great significance to carry out research on enhancing permeability and efficient extraction technology of outburst-prone coal seams, form a geological theory of coalbed methane extraction, and ultimately develop a set of efficient coalbed methane extraction technology system integrating permeability enhancement and gas-driven production that is suitable for complex geological conditions of coal seam mining.

2. Principle of Reduced-Oxygen Air Preparation

During the process of injecting medium and high wind pressure gas, the oxygen content in the air is reduced by corresponding membrane separation or pressure swing adsorption and other technical means to be lower than the safe oxygen content for coal mine production, thereby obtaining the oxygen-reduced air required for gas drive. According to the results of explosion characteristic experiments and considering the influence of various factors on the safe oxygen content, the oxygen-absorbing and oxygen-releasing agent oxygen-reduced air safety control technology proposed in this study is to control the oxygen content in the injected gas below 8% and set up an oxygen content safety early warning mechanism in the injection system to continuously monitor the oxygen content in the air compressor, injection pipeline and production well gas. Currently, in the process of injecting medium and high wind pressure gas, the required oxygen-reduced air is mainly obtained through membrane separation and pressure swing adsorption methods.

(1) Membrane separation method takes advantage of the different solubility of oxygen and nitrogen in the membrane, as well as the larger diffusion coefficients of water vapor and oxygen. When using membrane separation to produce oxygen-reduced air, water vapor and oxygen will pass through the membrane before nitrogen. By utilizing the pressure difference on both sides of the membrane, air is divided into an oxygen-rich gas portion with a higher oxygen content and an oxygen-reduced air portion with a lower oxygen content. This method can be used to produce oxygen-reduced air.

(2) Carbon molecular sieve pressure swing adsorption. By taking advantage of the selective adsorption difference of carbon molecular sieves for O2 and N2 molecules, compressed air is alternately injected into the carbon molecular sieve adsorption tower. O2 molecules have a smaller diameter and a faster diffusion rate on the surface of the carbon molecular sieve, thus entering the micro-pores of the carbon molecular sieve first. In contrast, N2 molecules with a larger diameter have a slower diffusion rate and enter the micro-pores less. This process achieves the separation of oxygen from the air. Through the principle of pressure swing adsorption, which involves pressurized adsorption and depressurized desorption, the air is separated in a cyclic manner to continuously and efficiently produce oxygen-reduced air.

(3) Besides the commonly used gas separation techniques mentioned above, there are many other methods that can be used to produce oxygen-reduced air, such as the ultra-low temperature air separation method. The ultra-low temperature air separation method involves compressing air and then converting it into a liquid state using heat exchange. By taking advantage of the different boiling points of the components, the air is deep-cooled and liquefied for separation and purification. By injecting oxygen-reduced air, the formation pressure can be effectively replenished, generating a gas drive effect. Additionally, since the O2 content in the injected gas is below the critical oxygen content, the risk of coalbed methane explosion can be completely eliminated. Due to its low oxygen content, oxygen-reduced air can reduce the corrosion of production equipment, downhole tubing, and pipelines to a certain extent.

The oxygen-reducing air material described in this article is an oxygen-absorbing and oxygen-releasing agent, characterized by being a mixture of one or more of ferrous oxide, cobalt oxide and additives, with cobalt oxide as the main component. It is required to absorb oxygen in the room temperature atmospheric environment, release oxygen when the partial pressure of oxygen in the environment is lower than that in the air or when the temperature is above 80°C, and then absorb oxygen again in the room temperature atmospheric environment, thereby achieving recyclability.

Ferrous oxide (FeO), cobalt oxide (CoO) and additives are important compounds in the study of oxygen absorption efficiency. Ferrous oxide is a black solid with magnetic properties, having a rock salt crystal structure, a density of approximately 5.7 g/cm³, a melting point of about 1369°C, insoluble in water but reactive with acids to form salts and water. It is easily oxidized by oxygen in the air to Fe_3O_4 (magnetite) or Fe_2O_3 (hematite). It can dissolve in acidic solutions to form iron ions. Additionally, ferrous oxide has a

certain thermal instability and can be disproportionated into metallic iron and Fe_3O_4 at temperatures below 575°C. It is produced by heating ferrous oxalate in an oxygen-free environment and is used in the manufacture of glass colorants. Cobalt oxide is a low-valent oxide of cobalt, and its color varies from grayish green, brown, pink to dark gray depending on the method of preparation and purity.

The reaction between ferrous oxide and oxygen is a typical redox reaction, and its detailed mechanism involves multiple steps. In this reaction, the iron ions (Fe2+) in ferrous oxide (FeO) are oxidized by oxygen (O2), while oxygen is reduced. During this process, the iron ions in ferrous oxide lose two electrons to become ferric ions (Fe3+), and at the same time, the oxygen molecules gain these electrons to form ferric oxide (Fe2O3). At the microscopic level of the reaction, the mechanism can be further explored. First, there is a strong chemical bond between the iron ions and oxygen ions in the lattice of ferrous oxide. When oxygen molecules approach the surface of ferrous oxide, due to the higher electronegativity of oxygen molecules compared to iron ions, they attract the electrons of the iron ions. In this process, the oxygen molecules are reduced to oxygen ions, and the iron ions are oxidized. With the transfer of electrons, the oxidation state of the iron ions increases from +2 to +3, forming ferric oxide. Additionally, from the kinetic perspective of the reaction, the reaction rate is influenced by temperature, pressure, and the concentration of reactants. At high temperatures, the molecular motion of reactants accelerates, increasing the collision frequency and thus speeding up the reaction rate. An increase in pressure makes it easier for oxygen molecules to come into contact with the surface of ferrous oxide, which also helps to increase the reaction rate. The higher the concentration of reactants, the greater the possibility of the reaction. Its equation can be expressed as:

$$FeO + O_2 \rightarrow Fe_2O_3 \quad (1)$$

The theoretical cobalt content of cobalt oxide (CoO) is 78.65%, and the oxygen content is 21.35%. Its melting point is 1935℃ and density is 5.7 - 6.79 g/cm³. The CoO crystal is face-centered cubic with a lattice constant of a = 4.24×10^{-10} m. The grayish green CoO powder tends to turn brown in air, while the pink CoO powder is relatively stable and will not form high-valent oxides even after long-term storage. At high temperatures, cobalt in cobalt oxide can dissociate from oxygen. At 1000℃, the dissociation pressure is 3.36×10^{-12} atm. Under heating conditions, cobalt suboxide is easily reduced to elemental cobalt by H, C or Co. Cobalt oxide can dissolve in acids and bases but is insoluble in water, alcohol and ammonia water. Meanwhile, cobalt oxide (CoO) is extremely harmful to water. Even a small amount of the product seeping into the ground can contaminate drinking water. Therefore, in this paper, the foaming process is used to avoid its harm to the environment.

The reaction mechanism of cobalt oxide with oxygen is a complex process involving multiple steps and intermediates. In this reaction, cobalt oxide (CoO) typically reacts with oxygen (O2) to form cobalt trioxide (Co3O4). This process can occur through various pathways, including the direct dissociation pathway and the hydrogen-assisted pathway. In the direct dissociation pathway of the reaction between cobalt oxide and oxygen, oxygen molecules directly interact with cobalt atoms on the surface of cobalt oxide. This process usually occurs at higher temperatures, where oxygen molecules (O2) dissociate on the surface of cobalt oxide (CoO) into two oxygen atoms, which then combine with cobalt atoms on the surface to form Co-O bonds. These newly formed Co-O bonds will further reorganize, eventually generating cobalt trioxide (Co3O4). This process does not require any external reducing agents or auxiliary molecules, and thus is called the direct dissociation pathway. In the hydrogen-assisted pathway, hydrogen (H2) acts as a reducing agent and participates in the reaction. In this process, hydrogen not only serves as a reducing agent but also promotes the dissociation of oxygen molecules. Hydrogen molecules dissociate on the surface of the catalyst into two hydrogen atoms, which then react with oxygen molecules to form water (H2O) and oxygen atoms. Subsequently, these oxygen atoms react with cobalt atoms on the surface of cobalt oxide, ultimately generating cobalt trioxide (Co3O4). The hydrogen-assisted pathway usually occurs at lower temperatures because hydrogen can reduce the energy required for the dissociation of oxygen molecules. Diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) can help observe surface-adsorbed oxygen molecules and possible intermediates, while X-ray photoelectron spectroscopy (XPS) can be used to analyze the oxidation state of surface cobalt atoms and their bonding with oxygen. The combined use of these techniques can provide important information about the reaction mechanism. In summary, the detailed mechanism of the reaction between cobalt oxide and oxygen is a complex process involving multiple variables and conditions. Its equation can be expressed as:

$$CoO + O_2 \rightarrow Co_3O_4 \quad (2)$$

Additives are substances used to improve the performance, processing properties or extend the service life of industrial products. Common industrial additives include preservatives, antioxidants, thickeners, emulsifiers, surfactants, etc. Their basic properties are as follows: Preservatives: Preservatives are used to prevent industrial products from being eroded and corroded by microorganisms and to extend the service life of the products. Antioxidants: Antioxidants can prevent industrial products from degrading due to oxidation during processing or use, thereby extending the stability and service life of the products. Thickeners: Thickeners can increase the viscosity of industrial products and improve their rheological properties, which are suitable for various processing requirements. Emulsifiers: Emulsifiers can make immiscible substances form emulsions, facilitating mixing and processing. Surfactants: Surfactants can reduce the surface tension of liquids, which is helpful for dispersion, emulsification, wetting, etc.

When iron(II) oxide (FeO), cobalt(II) oxide (CoO), and one or more additives react with oxygen, they will respectively generate iron(III) oxide (Fe2O3) and cobalt(III,II) oxide (Co3O4). Among them, iron(III) oxide, as a common oxide, usually undergoes reduction reactions with other compounds at high temperatures.

Cobalt(III,II) oxide is a cobalt oxide with mixed valence states. When heated, it undergoes redox reactions to generate cobalt(II) oxide (CoO) and oxygen (O2).

$$Co_3O_4 \rightarrow CoO + O_2 \quad (3)$$

This reaction takes place at high temperatures. During this process, every two molecules of cobalt (III) oxide (Co_3O_4) decompose to form six molecules of cobalt(II) oxide (CoO) and one molecule of oxygen (O_2). From a thermodynamic perspective, this reaction requires the absorption of heat because it involves the transformation of solid cobalt(III) oxide into solid cobalt(II) oxide and gaseous oxygen

molecules, which typically requires endothermic energy. At the atomic level, each molecule of cobalt(III) oxide contains three cobalt atoms and four oxygen atoms. Under high-temperature conditions, the crystal structure of cobalt(III) oxide is disrupted, causing the chemical bonds between cobalt and oxygen atoms to break, thereby forming cobalt(II) oxide and oxygen. In this process, every two molecules of cobalt(III) oxide decompose to produce six molecules of cobalt(II) oxide and one molecule of oxygen. This means that each molecule of cobalt(III) oxide generates three molecules of cobalt(II) oxide and half a molecule of oxygen. In other words, each molecule of cobalt(III) oxide releases 1.5 oxygen atoms during decomposition, which combine to form oxygen molecules. Additionally, cobalt atoms in cobalt(III) oxide exist in two oxidation states, Co(II) and Co(III), where Co(II) ions are surrounded by oxygen atoms in a tetrahedral arrangement and Co(III) ions are surrounded by oxygen atoms in an octahedral arrangement. During the decomposition of cobalt (III) oxide into cobalt(II) oxide, Co(III) may be reduced to Co(II), thereby forming cobalt(II) oxide. Therefore, this oxygen-absorbing and oxygen-releasing agent absorbs oxygen in the room temperature atmosphere, releases oxygen when the environmental oxygen partial pressure is lower than that in the air or when the temperature is above 80°C, and then absorbs oxygen again in the room temperature atmosphere, thus achieving recyclability.

3. Research and Development of Recyclable Oxygen-Reducing Material Ratios

During the use of oxygen-absorbing and oxygen-releasing agents, to comprehensively consider their oxygen absorption efficiency and economic effect, an appropriate proportion should be selected for blending. Therefore, in this section, orthogonal experiments were conducted on the material blending ratio for ferrous oxide, cobalt oxide and additives. Ferrous oxide was set at 1 mass part, 2 mass parts, 3 mass parts, 4 mass parts and 5 mass parts; cobalt oxide was set at 1 mass part, 2 mass parts, 3 mass parts, 4 mass parts and 5 mass parts; additives were set at 1 mass part, 2 mass parts, 3 mass parts, 4 mass parts and 5 mass parts. The mass part of oxygen consumed after the reaction was used as the standard. The test blending ratios of the oxygen-reducing materials are shown in Table 1.

Table 1. Orthogonal Table of Deoxygenation Material Proportions

Number	Ferrous oxide	Cobalt oxide	Additive	Oxygen consumption
1	1	1	1	0.85
2	1	2	3	1.55
3	1	3	5	2.25
4	1	4	2	2.45
5	1	5	4	3.15
6	2	1	5	1.5
7	2	2	2	1.7
8	2	3	4	2.4
9	2	4	1	2.6
10	2	5	3	3.3
11	3	1	4	1.65
12	3	2	1	1.85
13	3	3	3	2.55
14	3	4	5	3.25
15	3	5	2	3.45
16	4	1	3	1.8
17	4	2	5	2.5
18	4	3	2	2.7
19	4	4	4	3.4
20	4	5	1	3.6
21	5	1	2	1.95
22	5	2	4	2.65
23	5	3	1	2.85
24	5	4	3	3.55
25	5	5	5	4.25

This orthogonal test is a three-factor and five-level experiment. Therefore, variance analysis is needed to determine whether the changes of different factors in the experiment will lead to significant differences in the results, thereby helping to judge which of the three materials, ferrous oxide, cobalt oxide, and additives, has a more significant impact on the experimental results, and assisting in optimizing the experimental design and result interpretation.

Table 2. Three-factor variance analysis results of ferrous oxide, cobalt oxide and additives

Source of differences	Sum of squares	*df*	Mean square	*F*	*p*
Intercept	162.563	1	162.563	$1.45329331628595e^{32}$	0.00
Ferrous oxide	3.125	4	0.781	$6.984300827703769e^{29}$	0.00
Cobalt oxide	12.500	4	3.125	$2.7937203310814895e^{30}$	0.00
Additive	0.500	4	0.125	$1.1174881324326037e^{29}$	0.00
Residual	0.000	12	0.000		0.00

Table 2 presents the results of the three-factor analysis of variance for ferrous oxide, cobalt oxide, and additives. As shown in the table, the sum of squares for ferrous oxide is 3.125, for cobalt oxide is 12.5, and for additives is 0.5; the df values for ferrous oxide, cobalt oxide, and additives are all 4; the mean square values for ferrous oxide, cobalt oxide, and additives are 0.781, 3.125, and 0.125, respectively. Ferrous oxide shows significance ($F = 6.984300827703769e29$, $p = 0.000 < 0.05$), indicating the existence of a main effect, and ferrous oxide has a differential relationship with oxygen consumption. Cobalt oxide shows significance ($F = 2.7937203310814895e30$, $p = 0.000 < 0.05$), indicating the existence of a main effect, and cobalt oxide has a differential relationship with oxygen consumption. Additives show significance ($F = 1.1174881324326037e29$, $p = 0.000 < 0.05$), indicating the existence of a main effect, and additives have a differential relationship with oxygen consumption.

Figure 1 shows the comparison of the mean values of iron oxide and cobalt oxide. As can be seen from the figure, when the mass fraction is 1.0, the corresponding oxygen consumption is 0.85, 1.50, 1.65, 1.80 and 1.95 mass fractions; when it is 2.0, the corresponding oxygen consumption is 1.55, 1.70, 1.85, 2.50 and 2.65 mass fractions; when it is 3.0, the corresponding oxygen consumption is 2.25, 2.40, 2.55, 2.70 and 2.85 mass fractions; when it is 4.0, the corresponding oxygen consumption is 2.45, 2.60, 3.25, 3.40 and 3.55 mass fractions; when it is 5.0, the corresponding oxygen consumption is 3.15, 3.30, 3.45, 3.60 and 4.25 mass fractions.

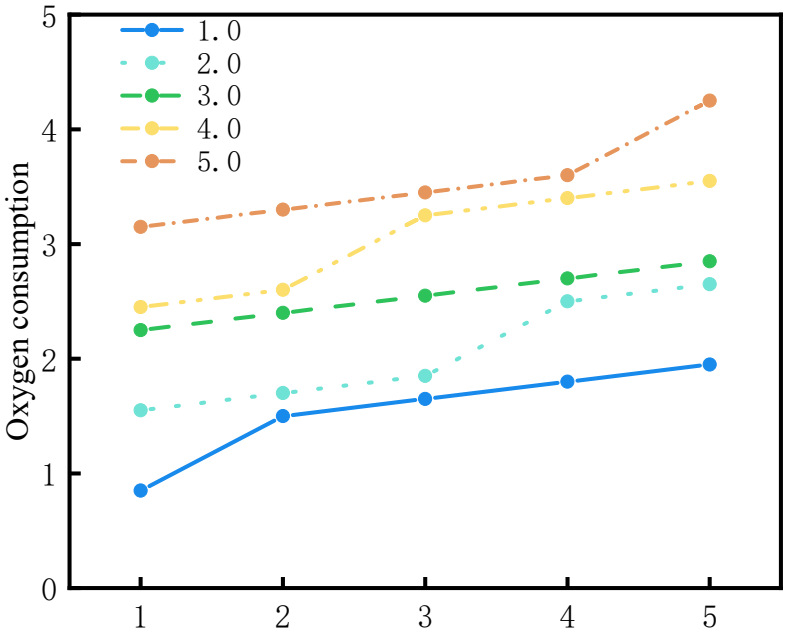

Figure 1. Comparison of the average values of ferrous oxide and cobalt oxide

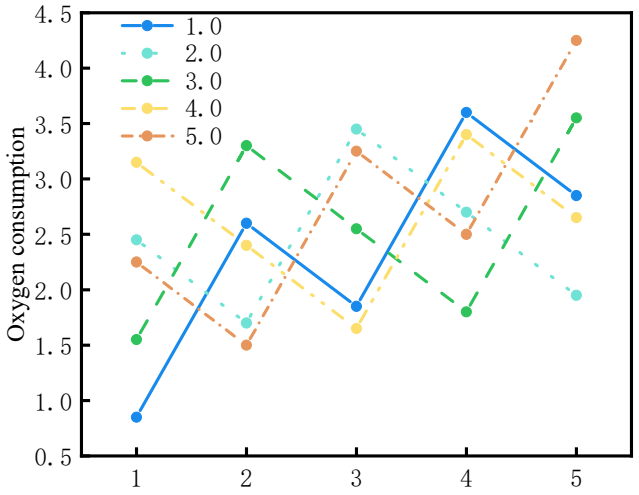

Figure 2. Mean Comparison Chart of Ferrous Oxide and Additives

Figure 2 shows the mean comparison chart of iron oxide and additives. As can be seen from the figure, when the dosage is 1.0 mass part, the corresponding oxygen consumption is 0.85 mass part, 2.60 mass part, 1.85 mass part, 3.60 mass part and 2.85 mass part; when the dosage is 2.0 mass part, the corresponding oxygen consumption is 2.45 mass part, 1.70 mass part, 3.45 mass part, 2.70 mass part and 1.95 mass part; when the dosage is 3.0 mass part, the corresponding oxygen consumption is 1.55 mass part, 3.30 mass part, 2.55 mass part, 1.80 mass part and 3.55 mass part; when the dosage is 4.0 mass part, the corresponding oxygen consumption is 3.15 mass part, 2.40 mass part, 1.65 mass part, 3.40 mass part and 2.65 mass part; when the dosage is 5.0 mass part, the corresponding oxygen consumption is 2.25 mass part, 1.50 mass part, 3.25 mass part, 2.50 mass part and 4.25 mass part.

Figure 3 shows the mean comparison chart of cobalt oxide and additives. As can be seen from the figure, when the mass fraction is 1.0, the corresponding oxygen consumption is 0.85, 1.85, 2.85, 2.60 and 3.60 mass fractions respectively; when it is 2.0, the corresponding oxygen consumption is 1.95, 1.70, 2.70, 2.45 and 3.45 mass fractions respectively; when it is 3.0, the corresponding oxygen consumption is 1.80, 1.55, 2.55, 3.55 and 3.30 mass fractions respectively; when it is 4.0, the corresponding oxygen consumption is 1.65, 2.65, 2.40, 3.40 and 3.15 mass fractions respectively; when it is 5.0, the corresponding oxygen consumption is 1.50, 2.50, 2.25, 3.25 and 4.25 mass fractions respectively.

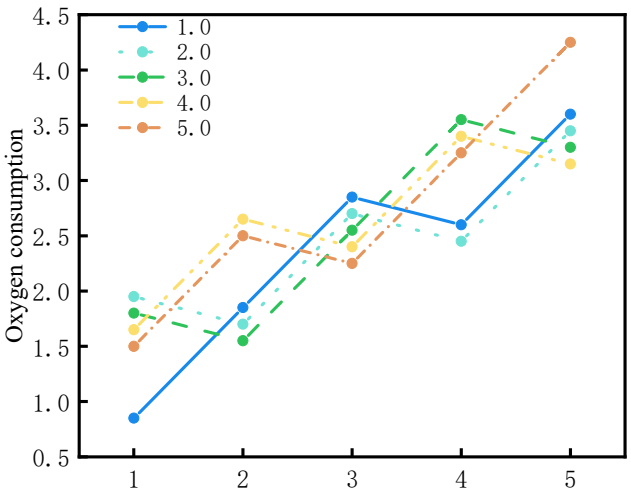

Figure 3. Mean Comparison Chart of Cobalt Oxide and Additives

Based on the data from the above three figures, the range of the three materials, ferrous oxide, cobalt oxide and additives, can be calculated, where $R_{FeO} = 1$; $R_{CoO} = 2$; $R_{additives} = 0.4$. Therefore, among the three materials, the order of priority for oxygen consumption from high to low is cobalt oxide, ferrous oxide and additives. In addition, the actual cost should be considered. Therefore, the best material ratio is cobalt oxide: ferrous oxide: additives = 4:2:1.

4. Conclusion

1) The research has proposed the oxygen-reducing air safety control technology with oxygen-absorbing and oxygen-releasing agents, aiming to control the oxygen content in the injected gas below 8% through self-developed oxygen-reducing air devices and other technical means, ensuring production safety. The oxygen-reducing air

technology helps to replenish formation pressure, generate gas drive effects, and effectively eliminate the risk of coalbed methane explosion and reduce equipment corrosion. The characteristics of the oxygen-absorbing and oxygen-releasing agents require them to absorb and release oxygen under specific conditions, achieving recycling. Through these technical means, the oxygen content in the injected gas can be effectively controlled.

2) The oxygen-reducing principle of the oxygen-absorbing and oxygen-releasing agents was studied and explained, and their ratio was determined through orthogonal experiments combined with economic effects as cobalt oxide: ferrous oxide: additive = 4:2:1.

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