Reason analysis and prevention measures of abnormal O₂ concentration in return air corner of super-long mining working face of shallow depth seam

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Abstract. Due to the occurrence conditions and mining characteristics of super-long working face in shallow depth seam, In normal mining process of the working face, various factors caused O₂ concentration reduced in the return air corner, including the raw coal absorbed a large number of oxygen and even coal oxidation spontaneous combustion consumed oxygen, the increase of working face tendency length, surface subsidence and leakage, air leakage in adjacent goaf, air leakage in the mined-out area behind and nitrogen injection fire prevention technology in goaf. In order to increase the oxygen concentration at return air corner, some effect measures were taken, such as optimizing the mine ventilation system, Increasing air leakage resistance in goaf, Changing the state of airflow field at the return air corner and reasonably arranging the position of nitrogen injection outlet in goaf. To create a safe working

1. Introduction
With the advancement of coal mining technology and the modernization of coal mining equipment in recent years, more high-yield and high-efficiency mines with a production capacity of 10 million tons have emerged. The length of their working face is over 2500 meters while the tendency length is more than 300 meters. Such super-long working faces are mainly distributed in Shaanxi Province and Inner Mongolia with good coal seam occurrence conditions. The layout of this kind of working face usually features stable coal seam occurrence conditions, low coal seam metamorphism, easy oxidation and spontaneous combustion, air leak in the shallow surface, fast recovery, and the loose goaf. Therefore, the oxygen concentration in the return air corner tends to be abnormally low, thus affecting the safe recovery in the working face.

2. Safe oxygen concentration in the mine
The 2016 Safety Regulations for Coal Mines stipulates that “in the inlet of the mining face, the oxygen concentration shall not be less than 20% while the concentration of carbon dioxide shall not exceed 0.5%”. However, the regulation only specifies the oxygen concentration in the inlet airflow of the mining face, but not that in the return air tunnel, the tail of the coal mining support, or the return air corner. In order to improve the working environment of coal mining face and ensure the safety of construction workers, the State Administration of Work Safety has formulated the Safety Regulations for Hypoxia Hazard Operation (GB8958-2006) to adjust the features of the anoxic working environment increasing the oxygen concentration of the dangerous anoxic operation from 18% to 19.5%. Based on the site of dangerous anoxic operation, the underground, culverts, mines, and waste
wells are classified as underground limited space. Therefore, according to the Safety Regulations for Hazardous Oxygen Operation, the oxygen concentration in the air return corner of the mine working face should not be lower than 19.5%. When working in a limited space, it is necessary to ensure sufficient oxygen concentration. When it drops to 18%, workers will experience wheezing, difficulty in breathing, and rapid heartbeat; when it drops to 15%, workers will be short of breath and slow, thus unable to work; when it drops to 10%-12%, workers will lose their senses, and even face death. In places with poor ventilation, the oxygen concentration may drop significantly. If operators enter rashly, they may face suffocation.

3. Cause analysis of abnormal oxygen concentration in return air corner of super-long working face

3.1 Oxygen adsorption of coal causes a decrease of oxygen concentration

Oxygen adsorption of coal has been recognized by many scholars and has been confirmed through experiment. Its process can be divided into physical adsorption and chemical adsorption, each taking different proportions in different oxidation stages. Physical adsorption plays a dominant role in the low temperature oxidation stage while chemical adsorption plays a dominant role in the low temperature oxidation stage. Jiang Neisi has proposed that the oxygen uptake of bituminous coal in the air can reach 0.4 mL/g under the normal temperature condition. Qi Xurao et al. have measured the oxygen uptake of coal in the low temperature stage using the chromatographic oxygen absorption method, proposing that the oxygen uptake of coal in the low temperature stage is related to the degree of coal metamorphism. At present, spontaneous combustion propensity identification of coal in China mainly adopts the method of chromatographic oxygen absorption identification, taking the physical adsorption oxygen amount of per gram of dry coal for 20 minutes at normal temperature (30℃) and under atmospheric pressure (101325 Pa) as the main index of classification. In daily production, the ventilation management of the single-head roadway and the closed-opening management of the non-fire source working face all verify the oxygen adsorption effect of coal. The daily output of the super-long 10-million-ton working face is up to 30,000-40,000 tons. In addition, due to the improvement of the mining mechanization, the coal body is relatively broken, and more coals are left in the goaf. Therefore, in the high-efficient high-production super-long working face, a large number of freshly exfoliated coal seams and the coal left in the goaf can absorb abundant oxygen in the wind flow and generate oxidation reaction, which greatly reduces the oxygen content in return air flow and the goaf, resulting in different degrees of decrease in air concentration in the return corner.

3.2 Effect of nitrogen-injection fire protection measures on the corner oxygen concentration in the goaf

Due to the large amount of coal lost in the goaf in the recovery process in the super-long working face, natural fire is more likely to occur. Combined with the characteristics of fast working speed, unstable goaf, and the large goaf area, it is considered that inert-gas-injection is the most effective means to reduce the oxygen concentration in the goaf and protect fire in the goaf. According to the Technical Specification for Nitrogen Fire Prevention for Coal Mines, the nitrogen concentration injected into the goaf should be no less than 97%. The amount of nitrogen injection at every working surface shall be calculated according to the following formula:

- \(Q_0\) — the amount of air leakage in the oxidation zone of the goaf, \(m^3/min\);
- \(C_1\) — the average oxygen concentration in the oxidation zone of the goaf, which is taken as 14%;
- \(C_2\) — inerting index of fire prevention in the goaf, which is taken as the value of the critical oxygen concentration of coal spontaneous combustion, 8%;
- \(C_N\) — the nitrogen concentration of nitrogen injected, which is taken as 97%;
- \(K\) — the reserve factor, which is taken as 1.2 to 1.5.

The amount of air leakage in the oxidation zone is taken as 1% of the air supply volume in the
working face (2300 m³/min), then the nitrogen injection amount in the goaf is about 2300 m³/h. If all
the nitrogen in the goaf is leaked or is transferred to the return air corner, then safe ventilation is
required:
- Q₀—safe ventilation volume in the workplace, m³/min;
- Qₙ—maximum nitrogen leakage, m³/min;
- Cₙ—nitrogen concentration of the leaking nitrogen, %;
- C₁—the original oxygen concentrations in the working face or the roadway, which is generally
taken as 20.8 %;
- C₂—Safety oxygen concentration index in the workplace, %.
Since the oxygen concentration of the hypoxia hazard operation shall be no less than 19.5%, the
safe ventilation set to be 524 m³/min. Since the goaf adopts the open nitrogen injection, the nitrogen in
the goaf flows to the corner with the leaking air under the negative pressure ventilation condition of
the mine during nitrogen injection. If the air supply in the return air corner is low, the oxygen
concentration there will be abnormally low.

3.3 Influence of air leakage in goaf on oxygen concentration in air return corner
Air leakage in the goaf is mainly divided into air leakage in fissures due to surface collapse, air
leakage between adjacent goafs, and air leakage in the back goaf. The first one belongs to the outside
air leakage. The coal seam is shallow and thick in Shaanxi and Inner Mongolia, so the goaf tends to
collapse to form a wide range of air leakage passages, through which the surface air flows to the
working surface. The isolated coal pillars and connecting lanes in adjacent goafs are broken under the
pressure of the mine, thus forming a wind leakage passage. Due to the nitrogen injection, the depletion
of the residual coal, and the oxidation of the residual coal, there is a large amount of toxic and harmful
gases accumulated in the goaf. A positive pressure zone is formed in the enclosed area, and quantity of
toxic and harmful gas in the old goaf is poured into the return air corner under negative pressure
ventilation. In addition, since the roof of the goaf is unstable, part of the wind flows from the inlet to
the air return corner through the goaf during the mining process. Although the position of the air
leakage source and the form of air leakage are different, the return air corner, as the air leakage
junction of the goaf in the whole working face, will bring out the toxic and harmful gas with low
oxygen concentration and meet with the wind flow in the working surface, thus dilute the oxygen
concentration of the return air corner to a large extent, under the negative pressure ventilation
condition.

3.4 Influence of the tendency length of the working face on the oxygen concentration of the corner
The change in the tendency length of the working face directly affects the wind pressure in the inlet
and the outlet air passages, the propulsion of the working face, the air leakage in the goaf, and the
pressure distribution of the working face. Since the design wind speed of the coal mining face is
0.25-4 m/s, the wind flow is in a turbulent state. Based on the law of ventilation resistance:
- h—frictional resistance, Pa; α—friction coefficient of the roadway, kg/m³;
- L—length of the open-cut in the working face, m; U—parameter of the open-cut in the working
face, m;
- S—area of open-cut in the working face, m²; Q—air volume in the wellway, m³/S.
When the air supply volume of the working face remains unchanged, as the L increases, the
frictional resistance of the working face (or the pressure difference between the inlet and the outlet air
passages) increases linearly, resulting in a small increase in the air leakage. In actual production, as the
length of the working surface increases, the air supply volume also increases, and the frictional
resistance of the working surface and the pressure difference between the inlet and outlet wind
passages increase approximately in a parabolic relationship, resulting in a large increase in air leakage
in the goaf. Under negative pressure ventilation, the leaked air fully dilutes the oxygen in the return air
corner.

The tendency length of the working face has a great influence on the propulsion speed of the
working face, the air leakage in the goaf, the division of the goaf, the stress state and the damage law of the roof. As the length of the working face increases, its propulsion slows down, resulting in more oxidation time of the coal in the goaf. In addition, due to the increase of the air leakage, the range of oxygen distribution and the oxidation zone in the goaf will be expanded. That provides favorable conditions for spontaneous combustion of the residual coal, leading to more oxygen consumption in the goaf and more toxic and harmful gases. The leaked air in the goaf further dilutes the oxygen concentration in the return air corner.

3.5 Other factors
The wind in the mine ventilation system always flows based on the shortest path with the minimum wind resistance. Without any special ventilation measure, the fresh airflow is difficult to reach the end of the return air corner through the working face. So, the airflow at the end of the return airway is mainly caused by diffusion disturbance of the working surface and the air leakage, making this place easy to form an eddy current. The toxic and harmful gas from the goaf tends to bring the gas concentration in the return air corner above the limit and lower the oxygen concentration. In addition, the collapse the goaf roof under pressure and the toxic and harmful gases emitted by the underground diesel transport vehicles can influence the oxygen concentration of the working face to some extent.

4. Safety measures for preventing abnormal oxygen concentration in the air return corner

4.1 Optimize mine ventilation system
Optimizing the mine ventilation system can fundamentally solve or control the problems concerning mine ventilation resistance, air supply distribution, gas overrun, and coal spontaneous combustion prevention. The measures for reducing the O₂ concentration of the return air corner of the super-long working face are: 1) Increase the sections of the working face and the cross-entry tunnel, improve the uniformity of the working face bracket and the flatness of the coal wall, reduce the wind resistance during ventilation of the working face, reduce wind pressure on the two sides of the working face, and reduce air leakage in the goaf; 2) Close the old goaf of the adjacent working face, relieve the pressure relief through the connection roadway in advance, and reduce the flow of toxic and harmful gases in the adjacent goaf towards the working face; 3) Determine the technical parameters such as the length, the air volume, and the negative pressure of ventilation based on the calculation results of the wind resistance of the working face and the simulation of the spontaneous combustion of the goaf, and reduce air leakage of the goaf in the working face and the adjacent goaf.

4.2 Increase air leakage and wind resistance in goaf
All the toxic and harmful gases pass through the return air corner, the air leakage juncture of the goaf in the whole working face, severely diluting the O₂ concentration of the corner. Therefore, reducing air leakage in the goaf is an effective measure for reducing O₂ concentration. According to the law of air leakage resistance $h_L = R_L Q^n$, or $Q = n\sqrt{h/R_L}$ $(1 < n \leq 2)$, there are only two ways to minimize the air leakage, namely, reducing the pressure difference at both ends of the air leakage passage to achieve $h_L \to 0$, and blocking the air leakage passage and increasing its resistance to achieve $R_L \to \infty$. For the surface leakage in shallow coal seams, two measures can be taken: first, block the surface leakage channel to increase the wind leakage and wind resistance; second, pre-crack the coal seam roof to reduce the empty top area of the goaf and increase degree of collapse and wind resistance, thus reducing the air leakage in the goaf. As for the air leakage in the goaf inside the mine, two measures can be taken: first, build sandbag wall or the inject polymer expansion filling material on the upper and lower corners of the goaf to reduce air leakage; second, strengthen the support of the connection roadway, and seal all enclosed goafs related to the working face to control the amount of air leakage in the adjacent goaf.
4.3 Change the state of the wind flow field
The return air corner in the U-shaped ventilation of the working face is the main juncture of the leaked air in the goaf. Under the action of the normal air flow field, it has a lower flow rate and smaller air volume. Part of it is in the eddy state, so the low-oxygen-concentration gas is difficult to enter the main air flow, resulting in a remarkable decrease of the oxygen concentration in the return air. The following measures can be taken in order to avoid the eddy state: 1) Hang the wind curtain at the end of the working face to introduce part of the wind directly into the return air corner; 2) Install a negative pressure pumping system at the return air corner to introduce the toxic and harmful gas from the negative pressure goaf to the main return air flow through the pumping line. In addition, the negative pressure generated by the pump will change the wind flow state of the return air corner and bring in some fresh air, thus increasing the oxygen concentration of the return air corner gas.

4.4 Measures to reduce nitrogen injection in goaf
Due to the large area of goaf in the super-long working face, nitrogen injection is often used to prevent spontaneous combustion of residual coal. The following measures can be taken to reduce the influence of nitrogen injection on the oxygen concentration in the return air corner: 1) Increase nitrogen purity (greater than 97%), increase the volume ratio of effective nitrogen injection; 2) Determine the best nitrogen injection amount in the goaf according to the amount of residual coal, the spontaneous combustion tendency, the spontaneous combustion change of the coal, and the air leakage in the goaf in order to avoid gas spillage and unnecessary economic loss because of excessive injection; 3) Rationally arrange the position of nitrogen injection outlet within the oxidation zone, increase the time for nitrogen to stay in the goaf to prevent oxygen concentration decrease in the air return corner due to air leakage.

5. Conclusion
The exposed shallow-buried coal in the super-long working face absorbs a lot of oxygen, and even consumes oxygen through spontaneous combustion. The increase of the tendency length of the working surface directly affects the air leakage in goaf. Various factors such as collapse and air leakage in the surface, air leakage in adjacent goafs and the back goaf, and the gathering of injected nitrogen in the return air corner lead to lower oxygen concentration. By adopting effective measures such as optimizing the mine ventilation system, increasing the wind leakage resistance of the goaf, changing the state of the wind flow field of the return air corner, and rationally arranging the position of nitrogen injection outlet, the oxygen concentration of the return air corner can be enhanced, thus providing a safe working environment at the air return corner for the workers.

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