Hindawi
Mathematical Problems in Engineering
Volume 2019, Article ID 8356701, 10 pages
https://doi.org/10.1155/2019/8356701

Research Article

Oxygen Distribution and Air Leakage Law in Gob of Working Face of U+L Ventilation System

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Received 12 November 2018; Accepted 17 January 2019; Published 12 February 2019

Academic Editor: Rafał Stanisławski

In order to prevent and control coal spontaneous combustion effectively in the gob of U+L working face, the 30105 working face of Hanglaiwan mine was taken as the research object. The relationship models between oxygen concentration and burial depth of the two tunnels in the gob of U+L working face were established. The distribution of oxygen in the gob of the working face of U+L ventilation system was studied by field observation combined with numerical simulation. The results show that the air leakage in the gob is serious. There are a number of fluctuation areas where the oxygen concentration first decreases and then increases in the air intake side of the gob. The oxygen concentration peaked at 100m, 175m, and 245m, respectively, from the intake side of the gob. In the same position of the gob depth, the air leakage intensity on the intake side is generally higher than that on the return side, and the oxygen concentration on the intake side of the gob is slower than the return side. Oxygen concentration maintains at 5.09% when the depth of gob reaches 400m. Measures to prevent coal spontaneous combustion should be strengthened in the air intake side.

1. Introduction

The U+L type ventilation system is provided with three air tunnels on the working surface, one main and auxiliary intake air tunnel on one side and return air tunnel on the other side [1]. The U+L type ventilation system is mainly used for high-yield and high-efficiency mining face with large gas emission [2], which can significantly remove the gas accumulated in the upper corner and change the direction of wind flow in the gob [3–5]. Hong [6] harnessed the FLUENT software to simulate the gas distribution of U+L and double U type ventilation. It was found that the gas drainage effect of U+L type ventilation system was weaker than that of double U type ventilation system. Ding [7] used numerical simulation software to carry out a three-dimensional numerical simulation research on gas migration law in gob and verified the reliability of numerical simulation by similar material experiment method. Yang [8] established the physical model and mathematical model of the U+L and double U type ventilation systems and analyzed the gas distribution law under the two ventilation systems according to the simulation results. Yu [9] studied the distribution of gas flow field in gob and showed that the distribution of gas flow field in gob was asymmetrical. The position of gas accumulation area changed with the transform of ventilation parameters, and the degree of air leakage in gob could be evaluated according to the position of gas flow field. Dong [10] studied the influence of the return air tunnel on the gas flow field in the working face in the U+L ventilation system, indicating that the influence of return air tunnel on the gas flow field in the gob of working face is mainly reflected in the vicinity of upper corner. Pan [11] studied the distribution of oxygen fields by sampling the gas components in the gob and determined the distribution of the "three zones" in the gob. The air leakage in the gob of U+L type ventilation system is inversely proportional to the depth of gob [12]. Because there is an air tunnel adjacent to gob, the air leakage in the gob of U+L type face is more serious than that of traditional U type face [13], and the probability of spontaneous combustion in gob is higher.

Many scholars have used numerical simulation and field observation methods to study the multifield coupling of the gob in the U+L ventilation system, but mainly focused on the gas control and performance evaluation of different

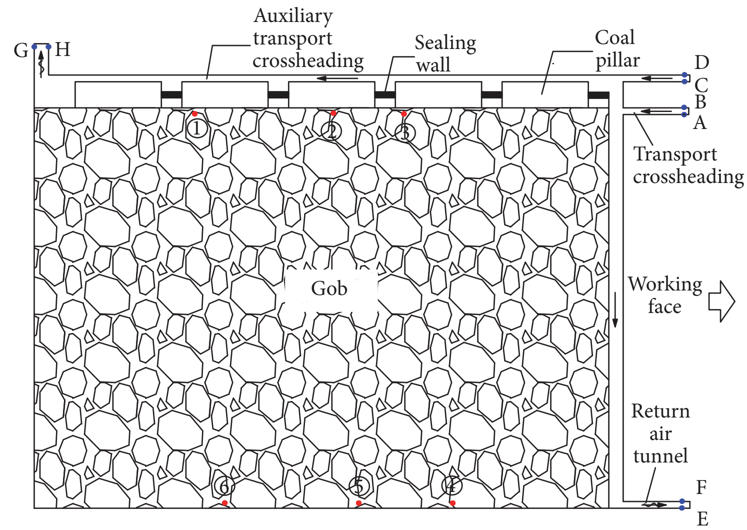


Figure 1: Working face model and measuring point arrangement.

ventilation systems. At present, there are few researches on the distribution of flow field and spontaneous combustion of left coal in the gob of U+L type working face. In this paper, the oxygen distribution and air leakage law in the gob of U+L type working face are studied by field observation and numerical simulation, which provides a theoretical basis for the prevention and control of spontaneous combustion of left coal in the gob of U+L type working face.

2. Gas Distribution Test in Gob

2.1. General Situation of Working Face. Hanglaiwan coal mine is in Shaanxi Province, China. As shown in Figure 1, the length of the 30105 working face of Hanglaiwan coal mine is 299.1m, the design length of the minable coal is 4313.3m, the average coal thickness is 9.2m, and the designed mining height is 5.0m. It is an easy spontaneous combustion coal seam. The percentage recovery of the working face is not less than 93%, the dip angle is 0.4 to 0.6 degree, and the mining is downward. The top surface of the working face is supported by hydraulic support, two channels are supported by anchor nets, single props are supported in advance, and gob is managed by all the falling methods. The transport crossheading of 30105 working face is used to carry out the task of entering the wind and transporting coal. The pedestrians and the trains are carried out in the auxiliary transport crossheading. After the mining face is finished, the auxiliary wind can be used as the return air tunnel of the adjacent working face. The section width of return air tunnel in 30105 working face is 5.4m, the height is 3.8m, the section width of glue transportation tunnel is 6.0m, the height is 3.8m, the section width of auxiliary transportation tunnel is 5.4m, and the height is 3.8m. The working surface air distribution is 1800m^3/min. There are coal pillars with a length of 60m and a width of 19.5m between transport crossheading and auxiliary transport crossheading. There are connecting tunnels between coal pillars, and working face is permanently closed after completion of the mining.

2.2. Gas Monitoring in Gob. The gas observation in the gob is carried out by a two-tunnel pre-buried pipeline method, which is sampled by a vacuum pump in the downhole and sent to the ground for chromatographic analysis. The measuring area of the design gob is 225m; the interval between adjacent measuring points is 75m; and the three measuring points in the two tunnels of the inlet and return are numbered 1 to 6, and they are observed at the same time. According to the actual conditions, 100m pipelines are added on both sides of the gob, with a total of 325m on both sides. The end of bundle tube is a filter probe. The outside of the bundle tube is protected by a steel tube of two inches. The probes are all raised by 1.5m. Place the probe in the protective iron box with holes to prevent the probe from being damaged. The end of bundle tube and piping arrangement are shown in Figure 2, and the entire pipeline is fixed below the coal wall. When taking the gas, connect the bundle tube to one end of the negative pressure gas sampler, open the negative pressure gas sampler and pre-pump for 2 minutes, and then connect the other end to the gas sampling bag to collect the gas. By carrying the sampling bag manually to the ground for chromatographic analysis, negative pressure gas sampler and gas sampling bag are shown in Figure 3. The measuring points are sealed when not taken and placed in a concealed location for protection.

3. Air Leakage Law Simulation in Gob

3.1. Simulation Parameters. Assuming that the gob is a porous medium of the same nature, the fluid in the set calculation area is incompressible, the flow of fluid is a steady flow, and the air seepage conforms to Darcy's law. It is assumed that loose coal body and air can be adsorbed to reach equilibrium under normal temperature and normal pressure, and the air

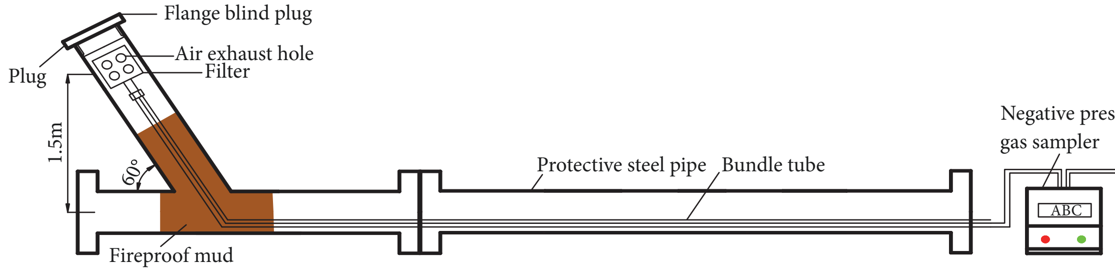


Figure 2: The end of the bundle tube and the piping arrangement.

Figure 3: Negative pressure gas sampler for use in field observations (left) and gas sampling bag (right).

quality does not change when the coal oxygen reacts. The components in the air diffuse from a high concentration to a low concentration according to Fick's law. The viscous and inertial resistance coefficients do not change in the vertical direction [14]; then the governing equations for the porous medium model in the gob are as follows:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial H}{\partial z}\right)=0 \quad (1)$$

$$\overline{Q}_x\frac{\partial C}{\partial x}+\overline{Q}_y\frac{\partial C}{\partial y}+\overline{Q}_z\frac{\partial C}{\partial z} = D_x\frac{\partial^2 C}{\partial x^2}+D_y\frac{\partial^2 C}{\partial y^2}+D_z\frac{\partial^2 C}{\partial z^2}-V(T) \quad (2)$$

$$\overline{Q}=-\frac{k}{\mu}\nabla H \quad (3)$$

$$V(T)=\frac{C}{C_0}V_0(T) \quad (4)$$

where $\overline{Q}_x$ is the air leakage strength of the gob, H is the pressure, and k is the absolute permeability. The gob permeability is considered being isotropic, and then $K_x = K_y = K_z$. According to the experimental calculation, the coal body takes k=2.6×10^{-8}m^2; μ is the air cohesive coefficient and $\mu = 1.7894\times10^{-5}kg\cdot m^{-1}\cdot s^{-1}$ at normal temperature. C is the oxygen mass concentration and the unit is $kg\cdot m^{-3}$, C_0 is the initial oxygen mass concentration, taking 21%; D is oxygen diffusivity at room temperature, taking $2.88\times10^{-5}m^2\cdot s^{-1}$, $V(T)$ is actual oxygen consumption rate, $V_0(T)$ is standard oxygen consumption rate, and $V_0(T)$ is $1.15076\times10^{-10}mol/(s\cdot cm^3)$ when the coal sample is at 35°C.

The physical model is established according to the actual situation of the working face. The origin of the coordinate axis is located on the return air tunnel of the gob in depth of 400m. The specific settings of the parameters required for the simulation are shown in Table 1.

3.2. Results Analysis and Discussion. Through the numerical calculation of the model, it can be seen that the oxygen distribution in the gob is shown in Figure 4, the oxygen distribution on the floor of the gob is shown in Figure 5, and the oxygen distribution section at different depths in the X, Y, Z directions of the gob is shown in Figure 6.

It can be seen from Figure 5 that the oxygen distribution on the floor of the gob is larger than that on the intake side of the gob with the increase of burial depth. The oxygen concentration on the intake side of the gob at the same depth is larger than that on the return side, which is consistent with the result of the literature [17]. Air leakage is more serious in the connecting tunnel near the working face. Currently, the susceptibility of coal spontaneous combustion has been ranked by using different laboratory methods to assess the risk of spontaneous coal combustion. These laboratory methods include the ignition temperature method, the adiabatic oxidation method, the activation energy method, and the heat release method [18, 19].

Table 1: Simulation parameter settings.

Category	Setting conditions
Boundary condition	AB, Velocity-inlet, Intake is air, wind speed v=1.39m/s, T=25°C
	CD, Velocity-inlet, Intake is air, wind speed v=1.72m/s, T=25°C
	EF, outflow
	GH, outflow
Coal wall in Gob	Non-slip velocity condition, u=v=0
Caving roof rock mass	Porosity, p=0.2
Sealing wall in connecting tunnel	Air leakage coefficient, m=0.1
Porosity of floating coal, Oxygen consumption rate	User Defined Functions (UDF) [15, 16]

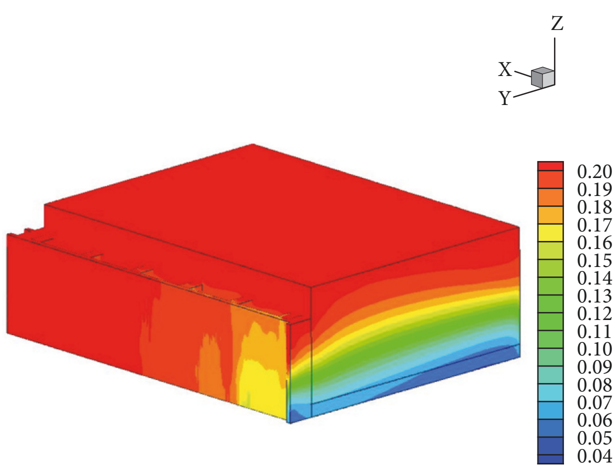


Figure 4: Oxygen distribution in gob at 30105 working face.

Oxygen is the key factor for coal spontaneous combustion. Polish scholars initially utilized oxygen consumption to indicate coal spontaneous combustion based on the certain correspondence between the oxygen consumption rate and the state of coal spontaneous combustion [20]. The oxygen concentration at the depth of 400m in the gob can reach 5.09%, which indicates that the gob has poor closeness and serious air leakage, and provides the condition for the spontaneous combustion of left coal. With the increase of burial depth, the oxygen concentration on the intake side decreases first and then increases, such as the position around 100m on the intake side. Oxygen concentration is higher at the shallow of the gob and air intake side of the connecting tunnel. The reason is that air leakage is relatively large at the air intake side of the gob, and the air leakage of the auxiliary transport crossheading through the connecting tunnel to the gob is also relatively serious. Therefore, the air leakage stoppage measures should be added at the air intake side.

The oxygen concentration distribution at different depth in the X, Y, and Z directions of the gob can be seen in Figure 6. In Figure 6(a), the oxygen concentration is the highest at the working face (X=400m), and the oxygen concentration is the lowest at X=0m (the deepest part of the gob). Since the coal in the gob will adsorb oxygen and react gradually with it, the physical and chemical adsorption of coal samples occur first after contacting, then the chemical reaction of coal oxygen occurs with the increase of temperature [21], and the oxygen concentration gradually decreases as the burial depth increases.

In Figure 6(b), Y=0m is the air return side, the maximum oxygen concentration is about 19.12%, and the lowest value is about 5.09%. However, at Y=299.1m, the air intake side of the gob, the oxygen concentration is decreased from 20.9% to 6.09% gradually. Comparing both, it can be seen that falling speed of oxygen concentration on the air intake side of gob is slower than that on the air return side and the air leakage on the air intake side is more serious. In Figure 6(c), as the vertical distance increases, the red area continues to spread deep into the gob, indicating that the floating coal of lowest level consumes the most percentage of oxygen. The oxygen concentration is maintained at about 20% in the area of Z=3~5m; it shows that the oxygen is basically not consumed and stored in the rock, which will provide conditions for the spontaneous combustion of the bottom float coal. The left coal of gob exposed to air undergoes an oxidation reaction through a process of adsorption and chemisorption [22]. If the heat produced by the oxidation exothermic reaction is not dissipated as fast as it is accumulated, there will be an increase of temperature and a thermal runaway event can ensue [23]. Therefore, in the coal mining process, the mining rate should be increased as much as possible [24, 25]. The left coal in the gob should be reduced to the greatest extent.

4. Oxygen Concentration Distribution in Gob

During the field observation process, when the burial depth of the 1# measuring point reaches about 300m, the oxygen concentration is 14%. And when the burial depth of the 6# measuring point is about 250m, the oxygen concentration is as high as 10%, indicating that the air leakage in the gob is serious. In order to verify the accuracy of the simulation results and realize the distribution of oxygen in the gob, numerical simulation method is used to determine the air leakage in the gob and compare the simulation results with the field observation data of the oxygen concentration distribution on both sides. The specific results are shown in Figures 7 and 8.

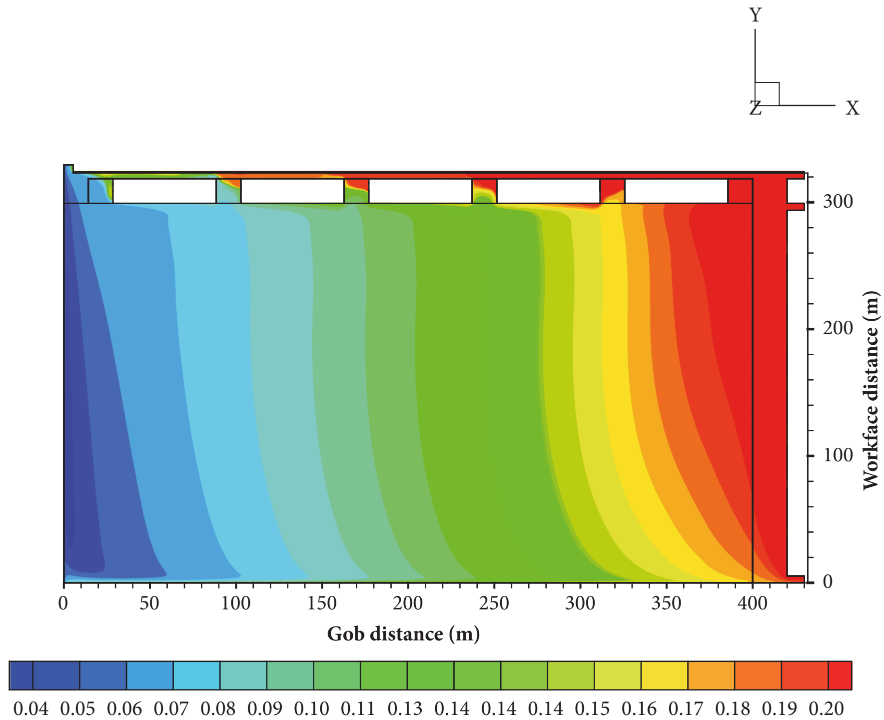


FIGURE 5: Oxygen distribution in floor of gob at 30105 working face.

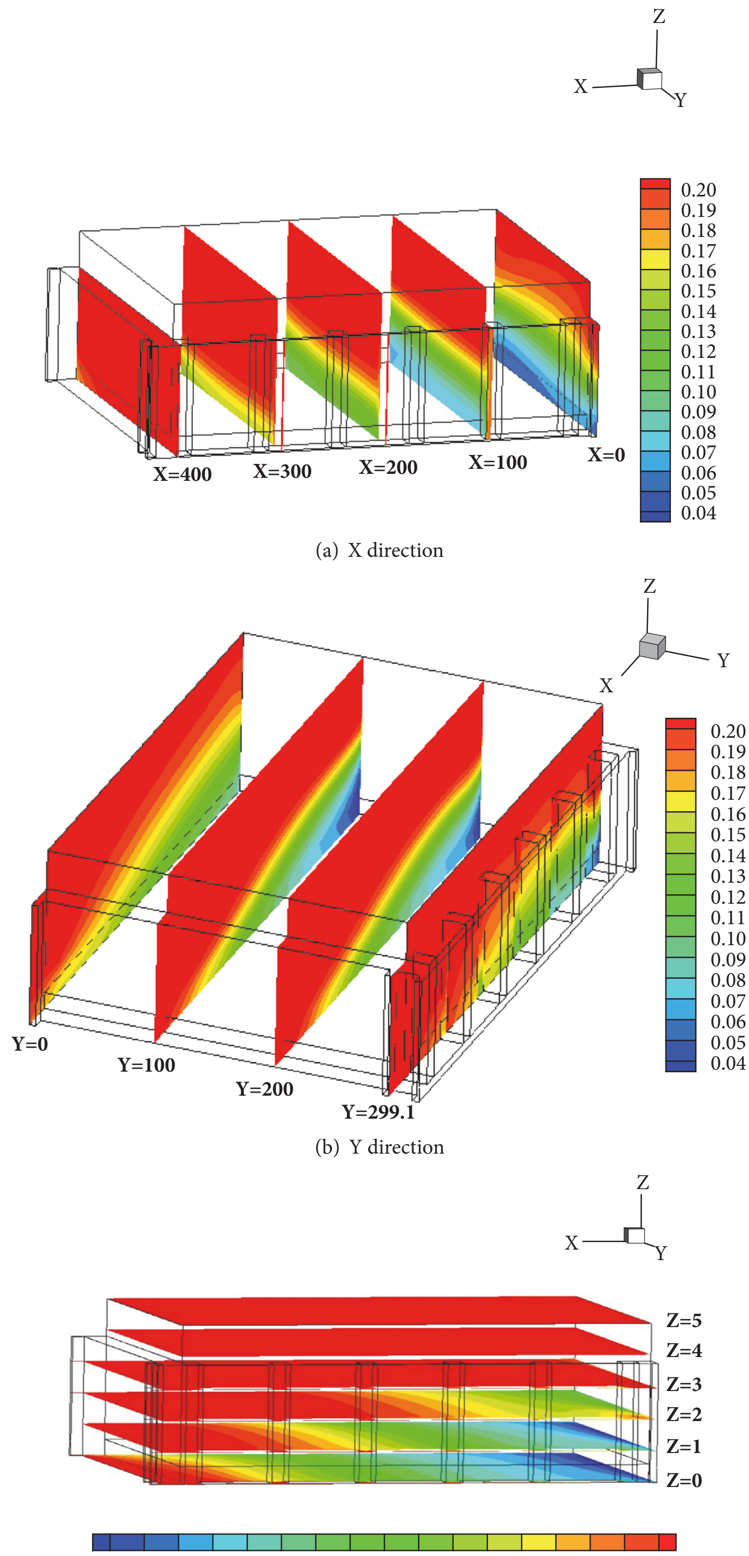
In Figures 7 and 8, the simulated oxygen concentration decreases gradually with the increasing of the burial depth, and the decrease rate of the oxygen concentration at the three measuring points on the air intake side differs greatly, while the difference between the results on the air return side is small. This is caused by the change of the ventilation system in the stope. The simulated oxygen concentrations on the air intake and air return sides are basically consistent with the results of the 3# and 4# measuring points on the site. It can be seen that the simulation results are in good agreement with the field measurements, which is well consistent with previous theoretical results [26] and the field observation in some similar coal mines [27].

In Figure 7, due to the serious air leakage on the air intake side, the oxygen concentration decreases continuously with the increase of depth in the 80m range on the air intake side. At the burial depth of 100m, 175m, and 245m, the oxygen concentration shows three peaks. This because the air leakage on the air intake side is large, and it is gathered into a peak here.

The fundamental reason for the reduction of oxygen is that the reaction between coal and oxygen consumes oxygen. Physical adsorption occurs first when coal and oxygen contact. Some surface active molecules in coal molecular structure absorb oxygen, form unstable carbon-oxygen complexes, and release a small amount of heat. In chemical adsorption, the oxygen consumption increases but the reaction rate is very slow. Some active structures will be activated and react with oxygen as the temperature rises, which will increase the reaction rate and produce certain heat and free radicals. The amount of heat generated by physical and chemical adsorption is mainly affected by oxygen concentration [28]. As the temperature continues to rise, more and more stable structures will gradually be activated, and the chemical reaction between coal and oxygen will gradually proceed. The stable structures (hydroxyl, aliphatic hydrocarbon, aromatic hydrocarbon, etc.) in coal molecule combine with the oxygen molecule to produce numerous of complex intermediate active products [29]. The intermediate active products can promote the coal-oxygen reaction, resulting in a rapid reaction, a significant heat and mass transfer, and a large amount of heat and gas.

It can be seen from Figure 7 that as the depth of the gob increases gradually, the oxygen concentration of each measuring point in the gob decreases continuously. The deeper the gob, the faster the falling speed. Comparing Figures 7 and 8, it is found that the oxygen concentration on the air intake side of the same location is generally higher than that on the air return side. Due to the combination of air seepage and oxygen dispersion, oxygen concentration nearby the air intake side of gob is high, which is consistent with the results of the literature [13, 24, 25, 30, 31].

In addition, three zones of the cooling, oxidation self-heating, and suffocation zones from the outside to inside of gob can be also distinguished in response to the O_2 concentrations [31]. The high temperature zones are mainly distributed in the gob between the 10-18% of O_2 concentration. Therefore, at the same time of strengthening monitoring, a series of fire prevention measures such as nitrogen injection, grouting, and injection molding must be implemented to eliminate the hidden danger in the early stage of development of spontaneous combustion of left coal on the air intake side



(a) X direction

(b) Y direction

(c) Z direction

Figure 6: Oxygen distribution sectional view at different depth in different directions in gob.

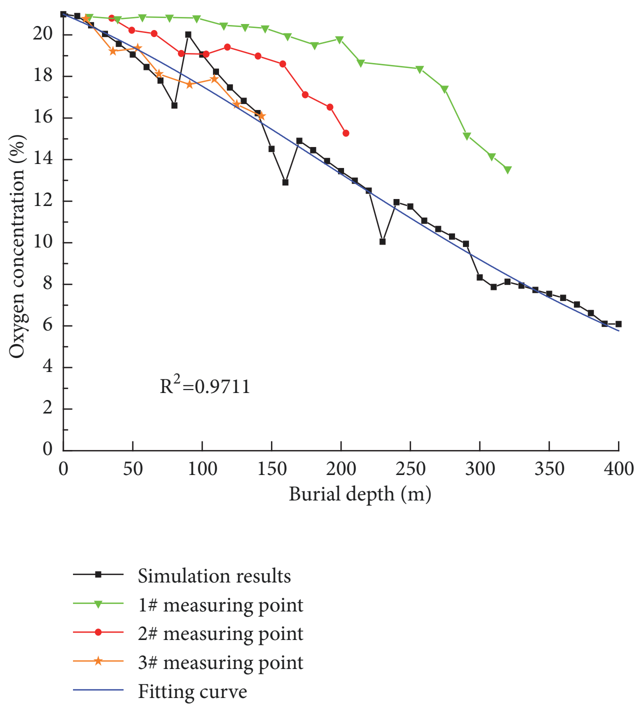


FIGURE 7: Comparison of simulated and measured oxygen concentration on the air intake side.

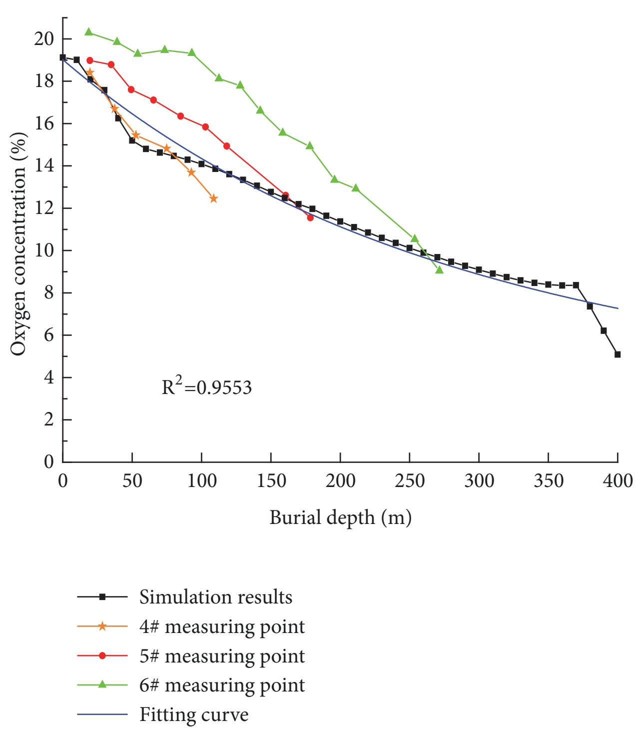


FIGURE 8: Comparison of simulated and oxygen concentration on the air return side.

of the gob [24]. The mathematical expressions for fitting the oxygen concentration and the burial depth using the origin software are shown in (5) and (6).

The relation between oxygen concentration y_1 (%) and burial depth x (m) in the air intake side is as follows.

$$y_1 = e^{(3.04413-0.00133x-0.000004759x^2)} \tag{5}$$

The relation between oxygen concentration y_2 (%) and burial depth x (m) in the air return side is as follows.

$$y_2 = e^{(2.94544-0.00296x+0.0000013787x^2)} \tag{6}$$

5. Change Law of Air Leakage Intensity

It is assumed that the airflow flows only in the one-dimensional plane and the air leakage intensity in loose coal remains unchanged. The relation between air leakage intensity and oxygen concentration is

$$\overline{Q}\left(\overline{x_i}\right) = \frac{V_{O_2}^0\left(x_{i+1}-x_i\right)}{C_{O_2}^0 \ln\left(C_{O_2}^i / C_{O_2}^{i+1}\right)} \tag{7}$$

where $C_{O_2}^0$ is the oxygen concentration in the fresh airflow and takes $9.375 \times 10^{-6} mol/cm^3$; $V_{O_2}^0(T)$ is the oxygen consumption rate when the coal temperature is T and the oxygen concentration is 21%, $mol/(s \cdot cm^3)$, $\overline{Q}(\overline{x_i})$ is the air leakage intensity in the gob, $cm^3/(s \cdot cm^2)$, and x_{i+1} and x_i are the two points of the gob to the distance of the working face, m. The oxygen consumption rate of the coal sample at 35°C is $1.15076 \times 10^{-10} mol/(s \cdot cm^3)$. In order to make the law more obvious, using the field 1# and 6# measuring point data, the distribution of the air leakage intensity at different positions in the gob and the three-dimensional distribution map are shown in Figures 9 and 10.

In Figure 9, the air leakage intensity is the largest on the intake side, followed by the middle of the gob and the smallest on the return side. The air leakage intensity decreases continuously from the air intake side through the central gob to the air return side, and the air leakage intensity of the air intake side of working face is about 4 times that of the air return side. In the range of 80m, the air leakage intensity is maintained at a large value, and when the burial depth is greater than 80m, the air leakage intensity is suddenly reduced.

In Figure 10, the air leakage intensity decreases with the burial depth increases, but as the burial depth increases, there are many local convex areas at the air leakage side. The most obvious is 100m away from the working face in the air intake side; the air leakage intensity appears at a maximum. This is due to the presence of the air intake side connecting tunnel so that the air leakage of the gob is greater than the surrounding point at the air intake side. In the same position of the burial depth, the air leakage intensity on the air intake side is generally higher than that on the air return side, which is consistent with the result that the existing oxygen concentration changes with the depth of the previous analysis. The air leakage intensity at the upper and lower sides of the gob is obviously larger than that in the middle of the gob. Furthermore, the deeper the place of airflow is in the gob, the smaller the intensity of air leakage is [32]. Due to the presence of coal pillars during the advancement of the working face,

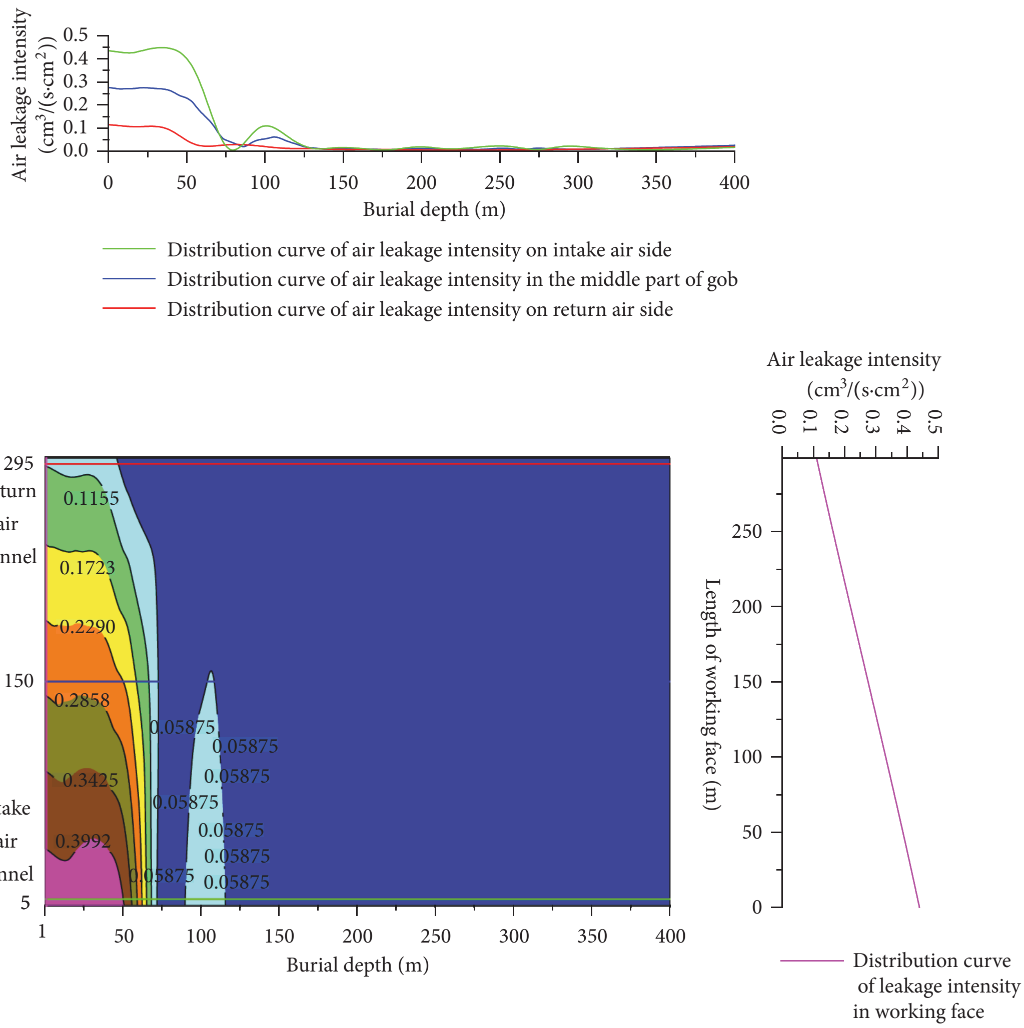


Figure 9: Distribution of air leakage intensity in gob.

the inner roof of the gob cannot be caving for a long distance and the roof of the gob adjacent to the two tunnels cannot be completely caving, resulting in a large void in the gob. The sealing of concrete and loess makes the connecting tunnel covered by the gob poorly sealed and the combined effect of the two causes serious air leakage in the gob.

The distribution of flow field in gob is very complicated, which is not only influenced by geological conditions such as the coal seam and roof of working face, but also influenced by factors such as temperature of stope and gas emission of working face. Therefore, it is difficult to accurately simulate the flow field distribution in gob. However, oxygen distribution and air leakage intensity in gob can be simulated and determined qualitatively, which has great influence in guiding the adoption of fire prevention and extinguishing measures on the working face.

6. Conclusion

(1) Taking the 30105 working face of Hanglaiwan mine as the research object, the numerical model of the mined area of U+L working face was established, and the gob of the model was verified based on the field observation results. On the air intake side of the gob, there are numerous fluctuations in the oxygen concentration that decrease first and then increase. When the depth of air intake side reaches 100m, 175m, and 245m, respectively, the oxygen concentration appears to be the maximum. The bottom floating coal at Z=0m has the most severe oxygen consumption, and the oxygen consumption in the rock formation of 3~5m from the bottom is very small, which will provide conditions for spontaneous combustion of left coal.

(2) Under the influence of auxiliary transport crossheading, the gob of U+L type working face has poor impermeability. In the same burial depth, the air leakage intensity on the air intake side is generally higher than that on the air return side, and the oxygen concentration on the air return side of the gob decreases faster than that on the air intake side. When the depth of the gob reaches 400m, the oxygen concentration can be maintained at 5.09%. Thus some measures of block wind should be strengthened on the air intake side of the gob to prevent spontaneous combustion of left coal.

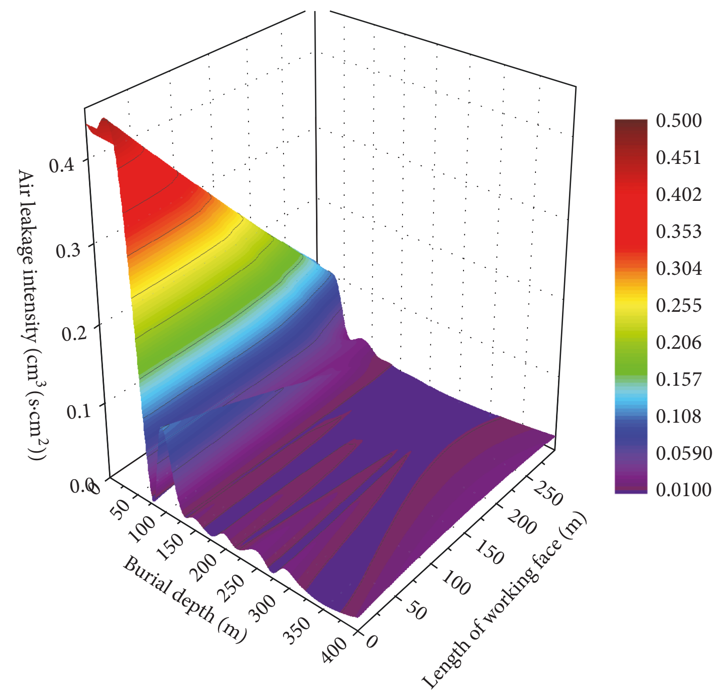


FIGURE 10: Three-dimensional distribution of air leakage intensity distribution in gob.

(3) Based on the results of field observation and numerical simulation, the relationship model between oxygen concentration and burial depth of the two tunnels in the gob of U+L working face was established. The relationships between the oxygen concentration y_1 (%) and y_2 (%) on the air intake and return sides and the burial depth x(m) are as follows.

$$
\begin{aligned}
y_1 &= e^{(3.04413-0.00133x-0.000004759x^2)} \\
y_2 &= e^{(2.94544-0.00296x+0.0000013787x^2)}
\end{aligned} \tag{8}
$$

Data Availability

The data used to support the findings of this study are included within the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the Key R & D Project in Shaanxi Province (Grant Number 2018KW-035).

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