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Air Flow Movement Law in Working Face and Gob with Roof-Cutting and Pressure-Releasing Mining: A Numerical Simulation and Engineering Verification

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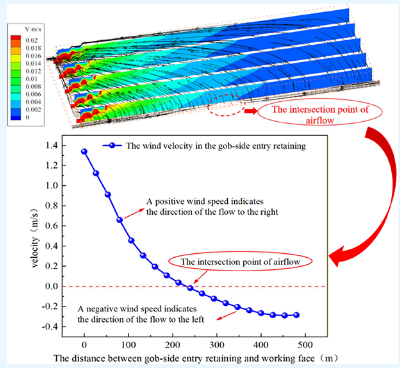
ABSTRACT: In comparison to traditional longwall mining, "roof-cutting and pressure-releasing" mining along gob-side entry retaining changes the permeability of the gob, as well as the pressure-relief characteristics and caving mode of the overlying strata. These changes are a result of the interaction of these factors, which also changes the boundary condition of the gob and the airflow movement law of the working face and the gob. In order to study the law of air flow movement in the working face and gob under the "roof-cutting and pressure-releasing" mining along gob-side entry retaining, the permeability model of gob was established under the engineering background of the 21,304 experimental working face of Chengjiao coal mine, then using fluent numerical simulation software, the movement law of air flow in working face and gob is simulated. The results show that the law of air leakage is much different from that of traditional longwall mining, and there are two main air leakage routes, First, most of the airflow will flow directly into the gob-side entry retaining under the action of inertia, and it will collide with the air flow provided by the fan at the end of the gob-side entry retaining, and the air will leak in the gob along the airflow direction; second, when the remaining airflow flows to the working face, the air leakage is serious in the air inlet corner, and most of the air flow flows into the gob. In view of the air leakage area, the air leakage prevention measures are put forward, such as setting the baffle plate, hanging the wind shield at the corner, and blocking the wall of the roadway with guniting; the simulation results show that the air leakage area is obviously reduced, and it is consistent with the measured data. The simulation results can generally describe the law of air flow movement in the face and gob with "roof-cutting and pressure-releasing".



1. INTRODUCTION

From the 1960s to the beginning of the 21st century, the traditional coal mining method widely used in China can be summed up as "121 mining method."[1,2] It is also called the traditional longwall mining method; if mining a working face, it is necessary to excavate two parallel grooves first. When the mining of this working face is completed, a certain width of coal pillars must be reserved before mining the next working face. (Taking a traditional longwall 121 mining with U-type ventilation as an example, see Figure 1) The traditional "121 mining method" has been developed for many years, and it has become the most mature mining method in China. However, the coal pillars left by the "121 mining method" are almost irrecoverable, resulting in a serious waste of resources. In order to reduce resource waste and improve coal recovery rate, He Manchao, an academician of the Chinese Academy of Engineering, put forward the theory of "roof cutting shortwall beam" in 2008, a new type of nonpillar mining technology-"roof-cutting and pressure-releasing" mining technology with roadway retained was also born.[3,4] This advanced mining method transfers the stress by "cutting the roof" to relieve the pressure of the roof,[5] and then reserves a roadway of the

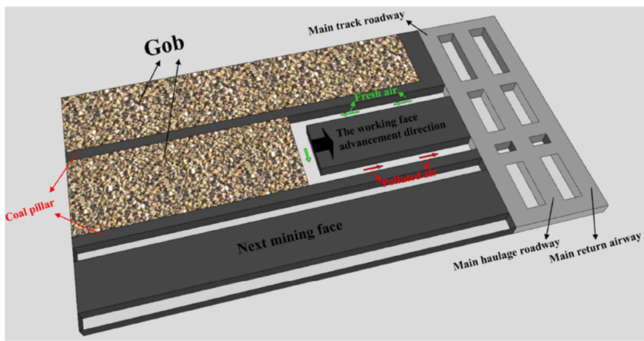


Figure 1. Traditional longwall 121 mining with U-type ventilation.

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working face through special support measures as the mining roadway adjacent to the working face in the future to serve the mining of the next working face.[6,7] (Taking a "roof-cutting and pressure-releasing" with retaining roadway working face with Y-type ventilation as an example, see Figure 2). This mining

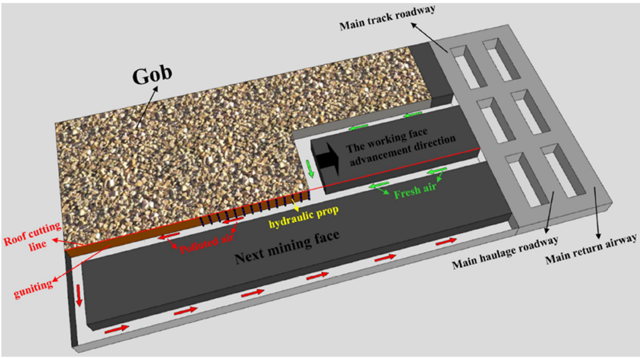

Figure 2. "Roof-cutting and pressure-releasing" mining with Y-shaped ventilation.

method is called "110 mining method", which requires only one roadway to be excavated for mining one working face without leaving coal pillars.[8] This technology not only realizes no pillar mining, reduces the waste of coal resources but also optimizes the stress of surrounding rock in the stope and reduces the amount of roadway excavation.[9−11] Nowadays, the global coal resource situation is relatively severe, and "roof-cutting and pressure-releasing" without coal pillar mining has become the trend of future coal mine production.[12]

Compared with the traditional longwall mining, the stress evolution of the overlying strata in the gob has changed in "roof-cutting and pressure-releasing" mining,[13] which results in the change of the pressure relief, caving and stress field of the gob roof; therefore, the permeability of the mined-out area changes.[14,15] In the process of "roof-cutting and pressure-releasing" mining, the roadway is directly adjacent to the gob. Without any blocking measures, the gob is "open" to the roadway, and the gas inside the gob is easy to escape from the gob to the roadway.[16] Under the influence of wind pressure, fresh air flow from the working face will also enter the gob and the roadway; this air leakage phenomenon will bring many safety hazards to production. Air leakage directly affects the period of spontaneous combustion of residual coal in the goaf and the distribution range of the "three zones of spontaneous combustion".[17,18] At the same time, the overrun of hazard gas in the working face and upper corner is also caused by air leakage.[19,20] Targeted blocking of air leakage channels is an important measure to ensure efficient production in coal mines. Therefore, it is particularly necessary to study the law of air flow migration under the "roof-cutting and pressure-releasing" mining.

With the development and application of the traditional longwall mining method for many years, scholars have done a lot of research on the airflow movement law of the traditional longwall mining face and gob and obtained a lot of academic results; it also ensures the safe and efficient production of longwall mining method for many years. Zhai et al.[21] used the field test and numerical simulation to study the law of air leakage and oxygen distribution in the gob of "U + L" ventilation system. Li et al.[22] use COMSOL Multiphysics to simulate the air flow and gas distribution in gob and reveal the law of air leakage and gas distribution in gob of fully mechanized mining face under the condition of "Y" ventilation. Gao and Yang[23] proposed that the gob grouting technology can reduce the permeability of the gob and improve the resistance of air diffusion, which can effectively reduce the risk of air leakage and spontaneous combustion in the gob. In view of the complicated air leakage in the traditional long-wall mining gob, Wang et al.[24] put forward a comprehensive method to prevent coal seam spontaneous combustion by balancing pressure, grouting and sealing, and filling in cracks. Li et al.[25] studied the influence of air inlet velocity on air leakage and gas distribution in gob. Aiming at the contradiction between gas accumulation and remaining coal oxidation in different ventilation rates, Cheng et al.[26] optimized the ventilation parameters by using the CFD simulation method and got the best scheme to control gas disaster and fire risk. Using the numerical simulation method, Zuo et al.[27] studied the relationship between the different advancing speed of working face and the area of the coal spontaneous combustion oxidation zone in gob under low air leakage velocity. Ma et al.[28] studied the oxygen concentration distribution in the adjacent gob by means of a similarity test and numerical simulation and determined the dangerous area of coal spontaneous combustion in the adjacent gob.

Because of the difference of mining methods, the research results of air flow movement in the traditional longwall mining face cannot be applied to the face with "roof-cutting and pressure-releasing". At present, only some scholars have studied the law of air flow movement in the face with "roof-cutting and pressure-releasing". Chen et al.[29−31] compared the air flow disturbance law in the gob under the traditional long-wall mining method and the "roof-cutting and pressure-releasing" mining method, and found out the different air leakage areas and the influence range of the three zones of spontaneous combustion in the two mining methods. By numerical simulation, Si et al.[32] injected CO_2 into the gob to dilute the concentration of O_2 based on the "Y" ventilation face in the gob-side entry, and the CO_2 injection rate which can minimize the oxidation range of the gob is obtained.

The existing research results are based on the two-dimensional plane, the three-dimensional permeability model of gob is not constructed, and the difference of air flow migration law in the vertical direction of gob is not reflected. In order to explore the applicability of "roof-cutting and pressure-releasing" working face and U-type ventilation mode, the serious air leakage area should be found out and the distribution range of three spontaneous combustion zones in and gob should be studied. Based on the 21,304 experimental working face of Chengjiao coal mine as the engineering background, a three-dimensional mathematical model of permeability in gob-side entry retaining face with "roof-cutting and pressure-releasing" is established, the law of airflow movement in working face and gob is simulated, and this work also studies the influence on the law of air flow movement in working face, gob, and gob-side entry retaining under the conditions of setting baffle at the entrance of gob-side, hanging the tent at the air inlet corner and blocking the retained entry with shotcrete. Finally, the validity of air leakage prevention measures and the accuracy of simulation are verified by comparing with the measured data on site. This research enriches the research results of air flow movement law in "roof-cutting and pressure-releasing" working face and

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provides certain theoretical reference for engineering application under similar conditions.

2. METHODS

2.1. Engineering Background. Chengjiao coal mine is located on the east side of Yongcheng, Henan province, Coordinates: 116° 17′30″ ~ 116° 25′21″ E, 33° 53′52″ ~ 34° 00′35″ N. The exploration area of the Chengjiao coal mine is about 103 km^2, the geological reserves are 725 million tons, the recoverable reserves are 402 million tons, and the designed production capacity of the mine is 5 million tons per year.

21,304 working face is the first mining face in the 13th mining area, the length of the working face is 180 m, and the length of the roadway is 1460 m. The thickness of the coal seam is 2.6−4.3 m with an average of 3.1 m. The dip angle of coal seam is about 1−7° with an average of 3°. The track roadway of 21,304 working face is designed as gob-side entry retaining, the roadway section is rectangular, the net section height is 2.8 m, and the width is 4.2 m and is designed as intake airway. The section of 21,304 belt roadway is also rectangular, the net section height is 2.8 m, the width is 4.2 m, and is designed as the return airway of the working face. The whole working face adopts the full air pressure ventilation mode, adopts the "U" type ventilation system of one-intake-one-return, and two FBD No 5.6/2 × 15 auxiliary fans are installed at the end of the track groove. The air supply is about 240 m^3/min. The air flow is through the gob-side entry and the working face into the return airway. The ventilation system of the working face is shown in Figure 3.

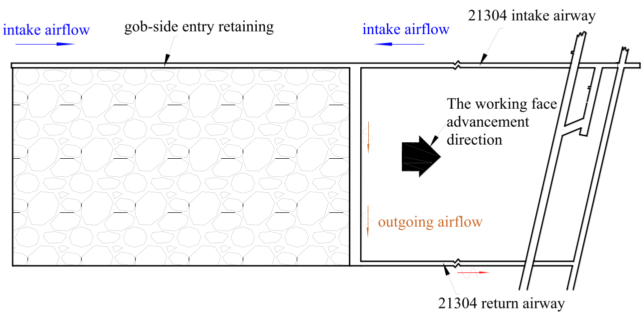

Figure 3. Ventilation diagram of 21,304 working face.

2.2. Physical Modeling. *2.2.1. Basic Assumptions and Boundary Conditions.* Considering the gob as a porous medium model, because of the complexity of the gob, the following assumptions are made:

(1) Assuming that the gas is incompressible, the standard $k-\varepsilon$ model under the turbulence model is chosen for the physical model, and the gas flow is steady;
(2) The influence of air temperature change on gas flow in gob is not considered;
(3) Because of the simple geological structure and the small dip angle of the coal seam, the whole gob is treated as a horizontal treatment;
(4) The inlet air flow is fresh air flow, which does not contain gas and does not consider the gas emission from the coal wall of the roadway;
(5) The actual shape of shearer and the hydraulic support is not considered, and the working face and roadway are regarded as cuboids.
(6) The boundary between the roadway and the gob is set as the internal boundary, the gas can flow freely, and the remaining boundary which is not set is the solid wall boundary by default. All the wall surfaces are nonslip boundary conditions. The near wall surface of the working face is treated by the standard wall function method, and the wall surface is treated by the adiabatic method;
(7) The porosity in the gob is controlled by the UDF because the technique of "roof-cutting and pressure-releasing" makes the roof fall controllable and makes the fall more sufficient; therefore, the porosity in the gob is regarded as no difference in the inclined direction of the working face (y direction), and the change of porosity is only related to the strike of the working face (x direction) and the height of the falling zone (z direction).

2.2.2. Physical Models and Parameters. According to the engineering practice, the gob-side entry retaining is 480 m, the inclined length of the working face is 180 m, the width of the working face is 6 m, the width of the intake and return airway is 4.5 m, the height is 3 m, and the height of the caving zone is 10 m. Two local fans are installed at the end of the gob-side entry to supply air to the gob-side entry retaining due to the use of forced ventilation in the entry. In order to simplify the physical model, an air inlet is set at the end of the gob-side entry, whose air quantity is equal to the air supply quantity of the local fan. The inlet boundary of air flow is the velocity inlet, the total air distribution volume is 1400 m^3/min, the inlet air velocity of 21,304 face is 1.5 m/s, the velocity of gob-side entry retaining is 0.3 m/s, and the boundary of the air flow exit is set as a free outflow, and the model parameters can be found in Table 1. The simplified three-dimensional numerical simulation model is shown in Figure 4.

Table 1. Parameters of the Simulation Model

parameter	value or condition
geometric size of working face: $x \times y \times z$ (m × m × m)	6 × 180 × 3
geometric size of gob: $x \times y \times z$ (m × m × m)	480× 180 × 10
height of caving zone (m)	13 m
velocity inlet 1: wind velocity provided by intake airway (m/s)	1.5
velocity inlet 2: wind velocity provided by ventilator (m/s)	0.3
outlet	outflow
internal condition of gob	porous zone
porosity, viscous resistance, inertial resistance	UDF

2.3. Mathematical Model of Permeability. The application of the "roof-cutting and pressure-releasing" mining method cancels the coal pillar and makes the roof fall more fully, so the porosity in the gob is regarded as uniform along the inclined direction (y direction) of the working face, and the

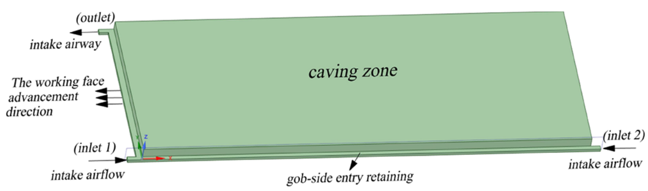

Figure 4. Geometric model used in simulation.

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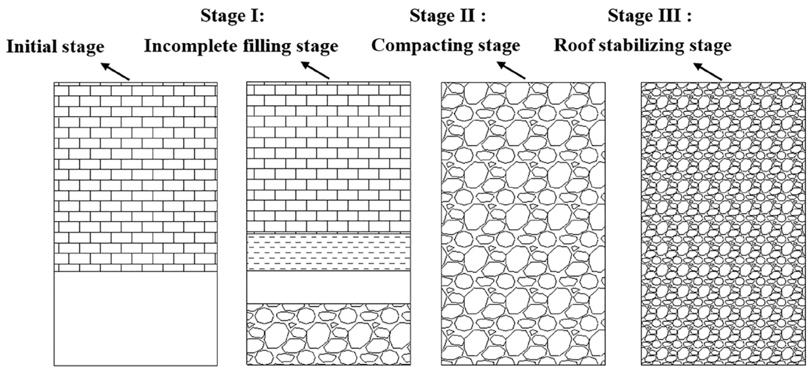

Figure 5. Filling process of roof caving in gob.

change of porosity in gob is only related to the strike of working face (x direction) and the height of the falling zone (z direction).

According to the law of strata behavior of roof, the gob is divided into three stages, the first stage is 0−50 m range of lagging working face, which is the incomplete filling stage, the second stage is 50−160 m range of lagging working face, which is the compacting stage, the third stage is the hysteresis face, which is more than 160 m range, which is the roof stability stage. The simplified diagram of the filling process in the goaf is shown in Figure 5.

Based on the two-dimensional plane porosity distribution formula of roof-cutting and pressure-releasing and considering that the porosity increases exponentially along the floor upward in the vertical direction, the three-dimensional porosity distribution formula of gob is as follows:

$$n = n_{xy} \times A^z \tag{1}$$

where n_{xy} is the porosity of the mined-out area near the floor, which is only related to the distance of the lagging working face; A is the constant coefficient, which is obtained from the empirical formula from 1.02 to 1.05; and z is the height of a certain point in the mined-out area, m.

According to previous studies, the porosity formula of the two-dimensional plane is as follows:[28]

$$n_{xy} = 1 - \frac{1}{K_p} \tag{2}$$

where n_{xy} is plane porosity and K_p is the bulking factor of the collapsed rock.

When the gob is not fully filled, the porosity presents different characteristics according to different heights. The expression of the gob porosity is derived as follows:

$$N = \begin{Bmatrix} \left(1 - \dfrac{1}{K_p}\right) \times 1.05^z, & 0 \le z < h_n \\ 1, & h_n < z \le 3 + h_m \\ 0.01, & z > 3 + h_m \end{Bmatrix} \tag{3}$$

When the gob is fully caving, the change rate of porosity along the vertical direction gradually decreases, adjusting the exponential function, and the expression of the gob porosity is derived as follows:

$$N = \left(1 - \frac{1}{K_p}\right) \times \left[1.05 - \frac{0.03(x - 50)}{110}\right]^z \tag{4}$$

When the mined-out area is stabilized and compacted, the change rate of the porosity decreases along the vertical direction, and the expression of the porosity of the mined-out area is derived by adjusting the exponential function:

$$N = \left(1 - \frac{1}{K_p}\right) \times 1.02^z \tag{5}$$

The permeability of the porous medium in gob depends on porosity and the average particle size of broken coal and rock in gob. From Kozeny−Carman's study of the relationship between permeability and porosity,[33]

$$e = \frac{D_p^2}{150} \times \frac{n^3}{(1 - n)^2} \tag{6}$$

where e is permeability, m^2; n is the porosity of the porous medium; and D_p is the average particle diameter, m, which is 0.3 m as observed in the field.

By substituting the porosity formula of gob in different stages into formula 6, the permeability formula of gob under the mode of "roof-cutting and pressure-releasing" can be derived. When the working face pushes 0−50 m and the gob is not fully filled, the expression of permeability in the stage I of gob is as follows:

$$e = \begin{Bmatrix} \dfrac{D_p^2}{150} \times \dfrac{\left[\left(1 - \frac{1}{K_p}\right) \times 1.05^z\right]^3}{\left[1 - \left(1 - \frac{1}{K_p}\right) \times 1.05^z\right]^2}, & 0 \le z < h_n \\ \dfrac{D_p^2}{150} \times \dfrac{0.95^3}{(1 - 0.95)^2}, & h_n \le z < 3 + h_m \\ 0, & z \ge 3 + h_m \end{Bmatrix} \tag{7}$$

When the working face pushes 50−160 m, the gob completely collapses and is in the process of gradual compaction, and the expression of permeability in the stage II of gob is as follows:

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$$e = \frac{D_p^{\ 2}}{150} \times \frac{\left\{\left(1 - \frac{1}{K_p}\right) \times \left[1.05 - \frac{0.03}{110} \times (x - 50)\right]^z\right\}^3}{\left\{1 - \left(1 - \frac{1}{K_p}\right) \times \left[1.05 - \frac{0.03}{110} \times (x - 50)\right]^z\right\}^2} \tag{8}$$

When the working face pushes over 160 m, the gob is in the stable compaction state, and the expression of permeability in the stage III of gob is as follows:

$$e = \frac{D_p^{\ 2}}{150} \times \frac{\left[\left(1 - \frac{1}{K_p}\right) \times 1.02^z\right]^3}{\left\{1 - \left[\left(1 - \frac{1}{K_p}\right) \times 1.02^z\right]\right\}^2} \tag{9}$$

After compiling the permeability formula of different stages into MATLAB, the permeability distribution model is obtained, which can three dimensionally change the rule of the gob permeability model in the collapsed area. The model diagram is shown in Figure 6.

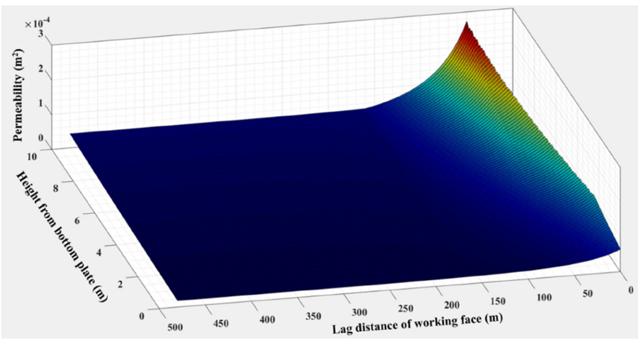

Figure 6. Permeability distribution of gob.

From Figure 6, it can be seen that the permeability of gob decreases with the increase of the distance of the lagging working face and increases with the increase of the distance from the floor, which is consistent with the change law of the porosity of the gob.

3. SIMULATION RESULTS AND ANALYSIS

According to the actual production conditions of the test working face, the air velocity of the inlet is 1.5 m/s, and the air velocity of the local fan at the end of the gob-side entry is 0.3 m/s, in the absence of any air leakage control measures, the simulation results are shown in Figure 7:

From Figure 7, it can be seen that the two air intakes and the deep area of gob and gob-side entry retaining are the areas with greater pressure, while the return air entry and the shallow area of the nearby gob are the areas with lower pressure, and the pressure gradient decreases gradually from air intakes and the deep area of gob-side entry retaining to return airway.

Combined with Figures 8 and 9, it can be seen that most of the air flow provided by the intake airway directly flows into the gob-side entry retaining and less air flow to the working face. The reason is that the gob-side entry retaining and the intake airway are directly connected; under the action of

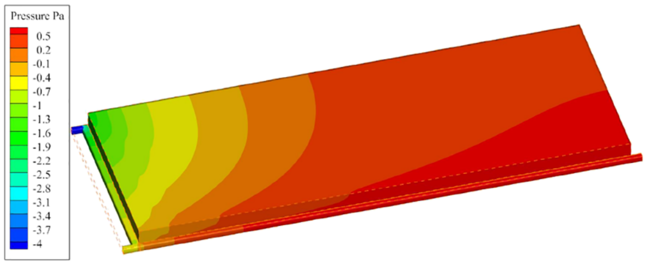

Figure 7. Pressure distribution without anti-leakage measures.

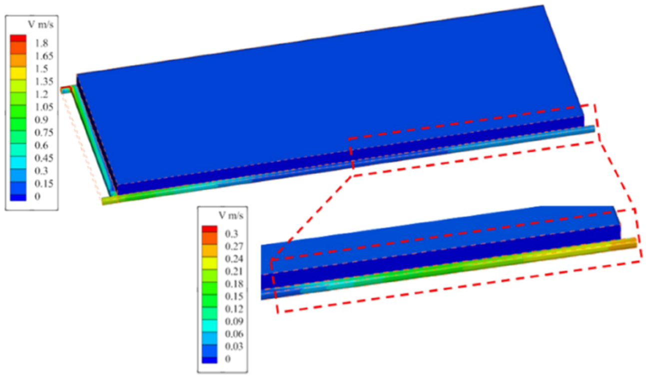

Figure 8. Velocity distribution without anti-leakage measures.

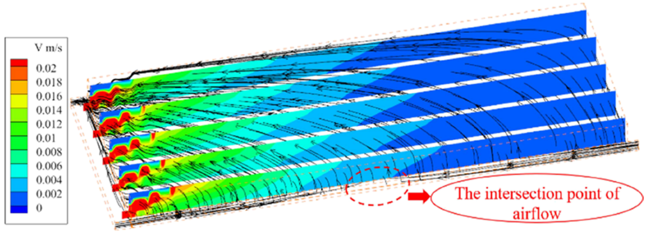

Figure 9. 3D wind velocity distribution in gob without air leakage prevention measures.

inertia, the air flow directly converges into the gob-side entry along the direction of the intake airway. The wind velocity of the air flow entering the gob-side entry retaining decreases along the opposite direction of the advancing face, while the fan at the end of the gob-side entry retaining provides the wind velocity of the air flow, which decreases along the advancing direction of the working face. The two air currents eventually form an intersection in the middle of the gob-side entry retaining. The reason is that the side wall of gob-side entry retaining near gob is formed by rock accumulation, under the influence of pressure gradient, the air flow entering gob-side entry will flow into gob and finally converge into working face and return airway.

From Figure 9, it can be seen that the air leakage velocity is relatively large in the gob within 50 m behind the working face, and the difference is very obvious in the vertical direction. The main air leakage passage is in the middle of the caving zone, the reason is that the mined-out area is not fully filled at this stage, and there is a big cavity in the middle of the caving zone, these voids make up the main air-leakage channels at this stage. After 50 m behind the working face, the air leakage velocity begins to decrease, and the difference in the vertical direction also begins to decrease because the gob is completely filled at this stage, and the caving zone is gradually compacted.

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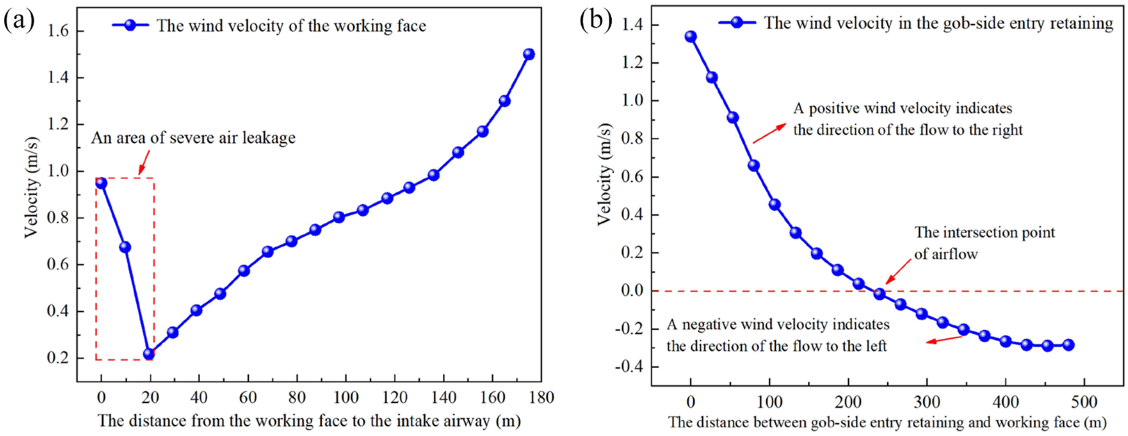

Figure 10. Wind velocity monitoring chart of gob-side entry retaining and working face.

3.1. Characteristics of Airflow Movement in the Working Face and Gob-Side Entry Retaining. Using CFD-Post to extract the data of fluent (see Figure 10a), by monitoring the change of wind speed in the incline direction of the workface, it can be known that the wind speed drops sharply in the range of 0−20 m in the inclined direction of the working face, and the air leakage rate is as high as 77%. When the airflow provided by the intake airway flows into the working face, because of inertia, it will flow directly into the gob-side entry retaining and the gob behind the working face; therefore, this area belongs to the serious air leakage area. The roof of the gob behind the working face did not completely collapse, resulting in large voidage at this stage, air flow along the leakage channel to the rear movement. The wind speed is compensated and increased in the inclined direction of the working face in the range of 20−180 m because the air leakage in the face and the gob-side entry flowed into the gob at this stage and then continued to return to the working face by the influence of air pressure and then along the direction of the working face flow back to the return airway.

CFD-post was used to extract the data of fluent (see Figure 10b). By monitoring the change of wind speed in the gob-side entry retaining, it can be known that the air flow provided by the intake airway and the air flow provided by the end of the gob-side entry retaining will intersect and hedge about 210−220 m away from the working face, making the wind speed approach to 0 m/s. In the left half of the intersection point of gob-side entry retaining, the air leakage law provided by the air inlet is as follows: there was a sharp air leak, and then, the air leak gradually weakened, the air leakage rate in the range of 0−100 m is as high as 65%. In the right half of the intersection point of gob-side entry retaining, the air leakage law provided by the fan at the end of gob-side entry retaining is as follows: the air speed loss is even along the path. The overall law of air leakage shows that air leakage exists in the whole gob-side entry retaining, and in the first half of gob-side entry retaining, the mined-out area is not fully collapsed, not fully filled, or the degree of compaction is low. There are more air leakage channels in the wall of the tunnel and gob, and the back half of gob-side entry retaining has less air leakage passage because of full caving of gob and higher compaction degree. Therefore, the air leakage law of the whole gob-side entry retaining appears as follows: “Sharply loss−Quickly loss−Slowly loss”.

According to the above research, there are some problems of air leakage in the process of “roof-cutting and pressure-releasing” working face along gob-side entry retaining. The air leakage makes it impossible to guarantee the effective air supply of the working face and the normal air supply of the gob-side entry retaining. Serious air leakage will increase the probability of accidents such as spontaneous combustion of coal in gob and over-limit of disaster gas. Therefore, in view of the obvious air leakage area, it is very necessary to take anti-leakage measures.

3.2. Characteristics of Air Leakage in Gob. As far as the spontaneous combustion characteristics of coal in gob are concerned, it is generally considered that, when the air leakage velocity of gob is greater than 0.004 m/s, the area is defined as the cooling zone. When the air leakage velocity in the gob is in the range of 0.00167−0.004 m/s, the region is defined as the oxidation zone. When the air leakage velocity of gob is less than 0.0016 m/s, the area is defined as the asphyxiation zone. It can be seen from Figure 11 that there are differences in the

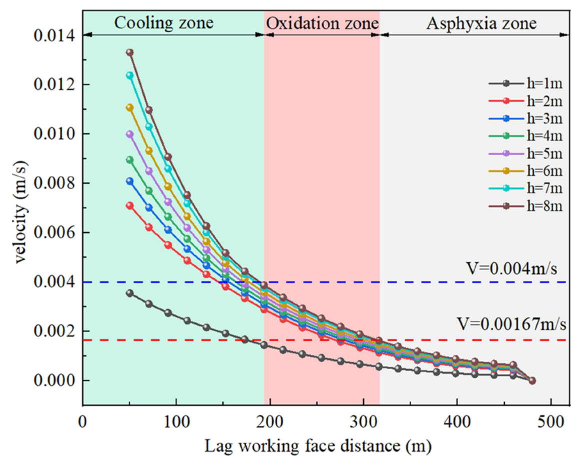

Figure 11. Air leakage velocity at different heights in fully filled gob.

air leakage velocity of different heights in the gob with the same distance behind the working face. When the air leakage velocity is the same, the higher the height is, the farther the lagging face is. Also, the difference of air leakage velocity in the vertical direction decreases with the increase of the distance of the delayed working face. In the absence of any measures to prevent air leakage, when the lagging working face is 0−190 m, it belongs to the cooling zone of the gob; when the lagging working face is 190−320 m, it belongs to the oxidation zone of

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the gob, and when the lagging working face is more than 320 m, it belongs to the asphyxiation zone of the gob. From the scope of three zones of spontaneous combustion, the problem of air leakage is serious in the face of "roof-cutting and pressure-releasing" along gob-side entry retaining, which brings hidden danger to production.

3.3. Characteristics of Air Flow Movement after Air Leakage Prevention. According to the simulation results, there is a serious air leakage phenomenon in "roof-cutting and pressure-releasing" mining along gob-side entry retaining, so it is necessary to take targeted measures to prevent air leakage. The air flow provided by the intake airflow mainly leaks in two directions, a part of the air flow is affected by the inertial action, and flows directly into the gob-side entry retaining, another part of air leakage is in the direction of the working face (0−20 m) corner into the gob. Based on this, first, a baffle is arranged between the air inlet roadway and the gob-side entry retaining to prevent the air inlet flow from flowing directly into the gob-side entry retaining. Second, hanging the wind tent at 0−20 m in the working face to reduce the air leakage near the inlet corner as much as possible. Finally, shotcrete is plugged into the wall of gob-side entry retaining next to the gob.

In order to realize the air leakage prevention measures used in engineering practice in the simulation software, through setting the permeability of interface in fluent, the effect of baffle, wind tent, shotcrete, is achieved. The air flow passing rate of the set baffle is 5%, the air flow passing rate of the air curtain is 10%, and the shotcrete is divided into two stages. The first stage is in the range of 0−50 m behind the working face (the gob is not completely collapsed), at this stage, the grouting cannot realize the completely effective grouting sealing, and the grouting effect is set to make the air flow pass rate 30%, the second stage is after the back of the face is more than 50 m (the gob is completely collapsed), and this stage shotcrete can be effectively blocked to a certain extent. The effect of shotcrete is set to make the air flow pass rate 1%. After setting the above conditions, the simulation results are as follows:

As can be seen from Figure 12, after setting up the baffle, wind tent, and shotcrete, because of the blocking effect of the

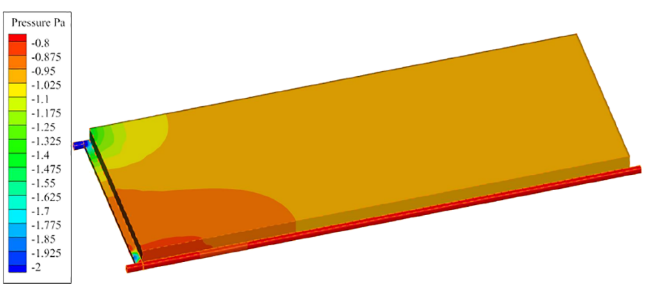

Figure 12. Pressure distribution after implementation of plugging measures.

baffle and the wind tent on the airflow, the airflow forms a vortex zone at the turning point of the intake airway and the working face, and the fluid fulcrum is centrifuged to form a high-pressure area on the outer side of the vortex zone and a low-pressure area on the inner side. In this area, air flow is along the right side of the face flow, and a part of the air will enter the gob behind the face. Therefore, along the inclined direction of the working face, the wind pressure has a transient attenuation area and then returns to normal, along the direction of the airflow slow attenuation. The area of relative high pressure is still the air entry, the next is the deep part of the gob-side entry retaining and gob, and the return air entry is still in the area of relative low pressure. The direction and trend of pressure reduction in the working face and gob have not changed, but the pressure in the gob has been greatly reduced, which shows that the air leakage into the gob has been greatly reduced.

As can be seen in Figures 13 and 14, when the baffle and the wind tent are set up, the air flow no longer flows directly into

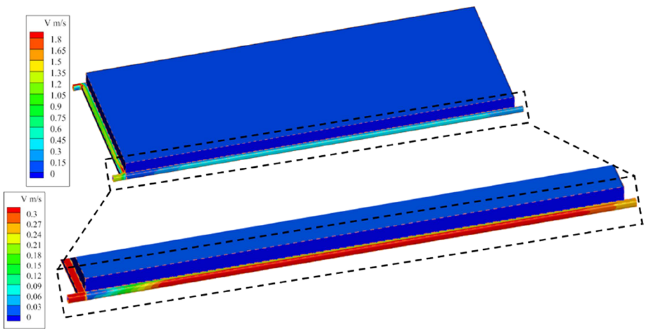

Figure 13. Wind velocity distribution after sealing measures were implemented.

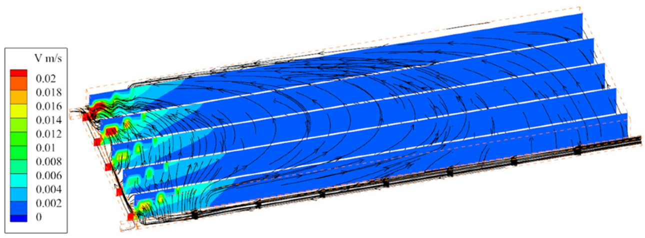

Figure 14. Three-dimensional wind velocity distribution in gob under air leakage prevention measures.

the gob-side entry retaining, the air distribution volume in the working face is ensured, and the air leakage into the gob is greatly reduced. After shotcreting the wall on one side of gob-side entry retaining, the air leakage in gob-side entry retaining has been greatly improved, and the air leakage in the second half of gob-side entry retaining has been greatly improved; however, there is still air leakage in certain areas behind the face due to the insufficient collapse of gob in certain areas behind the face, leading to large voidage, and there are still some air leakage channels.

It can be seen from Figure 14 that after setting up the baffle, wind tent, and shotcrete, the law of air leakage in the whole gob changed greatly, the "Slope-like" air leakage passage caused by the cavity still exists, and the air leakage is more serious, but it lags behind the working face more than 50 m; because of the shotcrete measure, the air leakage in the gob-side entry retaining and working face is restrained effectively, the air leakage situation has a remarkable improvement effect.

Using CFD-Post to extract the data of fluent (see Figure 15a), after setting up the baffle and the wind tent, the wind speed in the range of 0−30 m in the working face dropped sharply at first and then rose rapidly; this is because when the airflow in the intake airway enters the working face, it will go through a bend. Because of the blocking effect of the baffle and

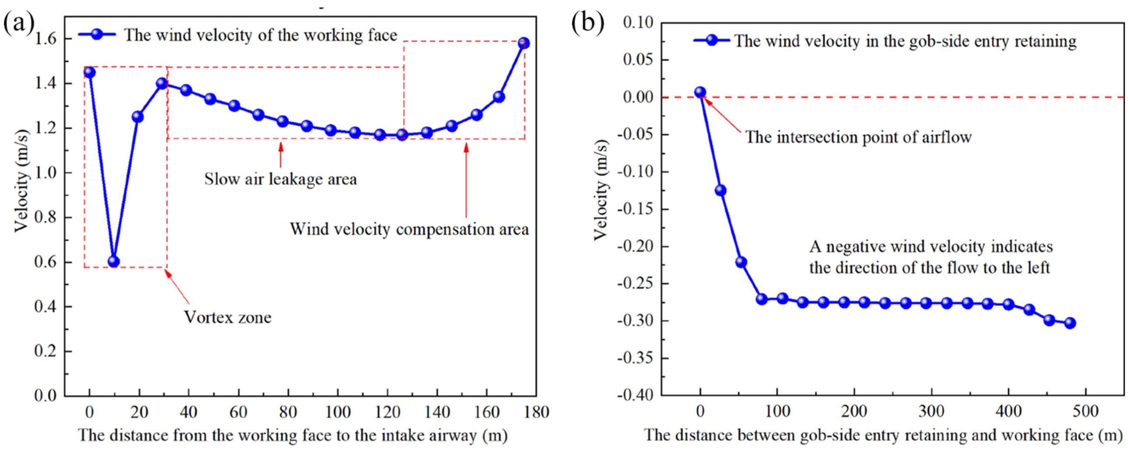

Figure 15. Wind velocity monitoring chart of retained roadway and working face.

the wind tent, the air flow is all close to the right side of the working face and tends to flow along the working face; after the air stream flows through this bend, the air stream will resume its normal flow. In the range of 30−125 m, there will be slight air leakage into the gob. In the range of 125−180 m, the air leakage of gob-side entry retaining and working face will rejoin the working face and finally flow into the return airway.

Using CFD-Post to extract the data of fluent (see Figure 15b), after setting up the baffle and shotcreting, the air flow provided by the intake airway will not flow into the gob-side entry retaining, and the air leakage quantity in the back half of the gob-side entry retaining (80−480 m range) is also greatly reduced; however, the air leakage is still serious in the first half of the gob-side entry retaining (0−80 m range), and the intersection point of the air flow is close to the position of the working face. The reasons are as follows: in the back half section (80−480 m range) of gob-side entry retaining, the internal compaction degree of the gob is higher; after shotcreting is applied to the side of gob in gob-side entry retaining, the wall formed by shotcreting will not be deformed and cracked because the collapse zone of gob will not have obvious change of compaction degree, it can better prevent the retained roadway air flow into the gob. In the first half of gob-side entry retaining (0−80 m range), the gob at this stage is adjacent to the working face, and the gob interior has not collapsed completely. After shotcreting, the gob is in the process of collapse and compaction, the side wall formed by shotcreting is easy to crack in the process of compaction, which results in part of air leakage channel.

3.4. Characteristics of Air Leakage in Gob after Air Leakage Prevention. As you can see from Figure 16, after setting up the measures of baffle, hanging wind tent and shotcrete to prevent air leakage, the airflow velocity in the gob decreases greatly, and the airflow velocity in the upper gob is still higher than that in the lower gob, but the difference is weakened. The range of the cooling zone in gob is reduced to 0−50 m in the lagging working face, the oxidation zone is reduced to 50−105 m in the lagging working face, and the asphyxiation zone is expanded to all gob areas after 105 m in the lagging working face. According to the change law of the three zones, the air leakage prevention measures are very effective, which can restrain the air leakage phenomenon in the gob to a great extent and prevent the coal spontaneous combustion in the gob to ensure safe and efficient production

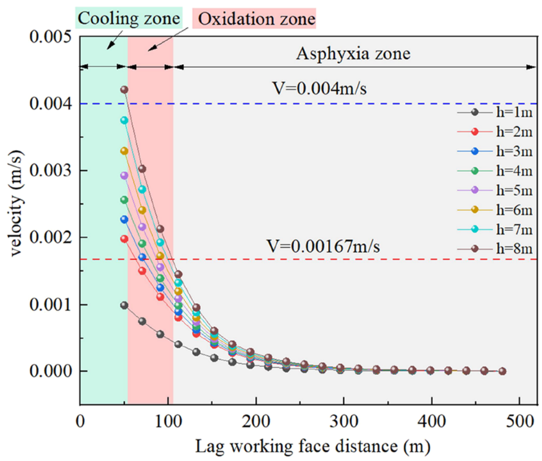

Figure 16. Air leakage velocity at different heights in fully filled gob after taking measures to prevent air leakage.

of "roof-cutting and pressure-releasing" mining along gob-side entry retaining.

4. ENGINEERING VERIFICATION

In order to verify the accuracy of the simulation, the technical measures of plugging the leakage by hanging the wind tent nearby the corner of the intake airway and shotcreting in the gob-side entry retaining are also adopted in the project, and collected the experimental working face and retained roadway air measured data, and compared with the simulation results.

In order to obtain the airflow movement of the whole working face, we set up the measuring points to monitor the air velocity in the intake airway, the gob-side entry retaining, the working face and the return airway, respectively. In gob-side entry retaining, a group of measuring points is set up every 50 m. The measuring points are shown in Figure 17. The testing results are shown in Table 2.

According to Figure 18a, along the inclined direction of the working face, the air leakage area also occurs in the range of 0−20 m, the airflow velocity slowly increases in the range of 20−160 m, and the airflow velocity rapidly increases in the range of 160−180 m. Compared with the simulation results, the air leakage area is the same, but the degree of air leakage is different. There is a certain error between the simulated data and the measured data, but it can be used to characterize the law of air leakage in the working face.

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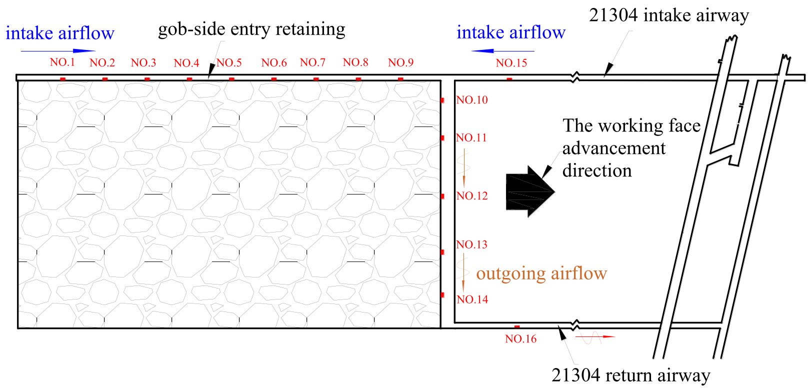

Figure 17. Arrangement of wind speed measuring points.

Table 2. Position and Data of Measuring Points

serial number	test site	group 1: average wind velocity (m/s)	group 2: average wind velocity (m/s)	group 3: average wind velocity (m/s)
1	distance from working face 435 m in gob-side entry retaining	0.29935	0.29935	0.30735
2	distance from working face 385 m in gob-side entry retaining	0.29056	0.29491	0.29926
3	distance from working face 335 m in gob-side entry retaining	0.28742	0.29154	0.29565
4	distance from working face 285 m in gob-side entry retaining	0.28548	0.28548	0.29146
5	distance from working face 235 m in gob-side entry retaining	0.28428	0.28428	0.28428
6	distance from working face 185 m in gob-side entry retaining	0.28289	0.28289	0.279
7	distance from working face 135 m in gob-side entry retaining	0.28221	0.27914	0.27299
8	distance from working face 85 m in gob-side entry retaining	0.28136	0.27022	0.27022
9	distance from working face 35 m in gob-side entry retaining	0.07831	0.11788	0.15026
10	working face 20 m from 21,304 intake airway	1.103963	1.068324	1.168991
11	working face 40 m from 21,304 intake airway	1.116713	1.148917	1.172037
12	working face 90 m from 21,304 intake airway	1.148917	1.222991	1.181852
13	working face 130 m from 21,304 intake airway	1.176676	1.057481	1.189704
14	working face160 m from 21,304 intake airway	1.223009	1.260231	1.205435
15	21,304 intake airway	1.467827	1.445889	1.533617
17	21,304 return airway	1.728259	1.741716	1.660951

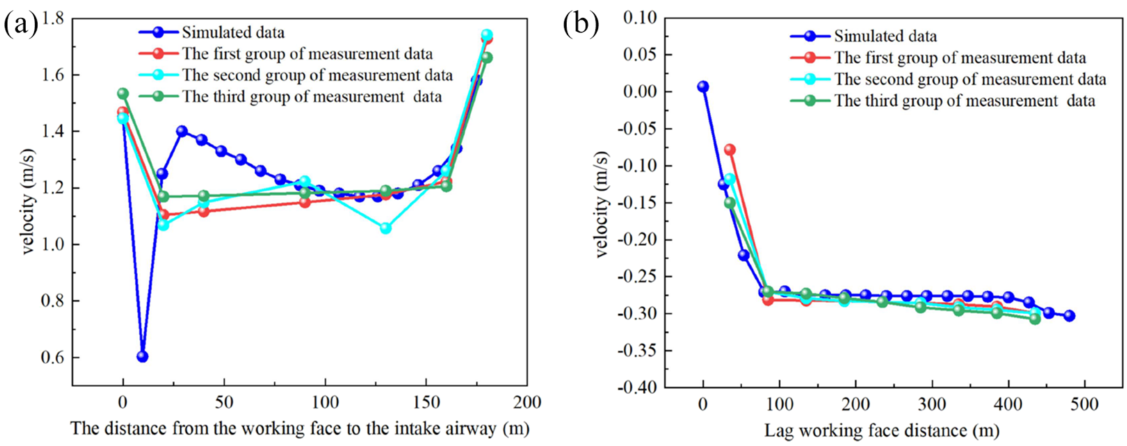

Figure 18. Comparison of simulated data and measured data.

From Figure 18b, it can be seen that in gob-side entry retaining, the airflow velocity decreases sharply in the range of 0−80 m behind the working face and slowly decreases in the range of 80−480 m behind the working face, and the airflow velocity is relatively stable. It shows that the serious area of air leakage in gob-side entry retaining is in the range of 0−80 m

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behind the working face. The three groups of measured data show this rule, and basically coincides with the simulated data. According to the situation of the broken stone side in the gob-side entry retaining (Figure 19), there are still big holes in the upper part of the roadway, although the roof can collapse in time, and the holes not fully filled and the gaps between the broken stones are the main passage of air leakage in the area of about 80 m behind the working face.

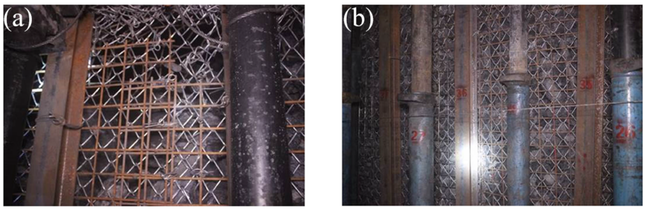

Figure 19. Situation of the crushed rock slope filling in the gob-side entry retaining section.

5. DISCUSSION

Taking the "roof-cutting and pressure-releasing" working face as the research object, the manuscript divides the interior of the gob into three stages according to the law of strata behavior: incomplete caving stage, compaction stage, and roof stabilization stage. A 3D mathematical model of permeability in gob is established with the bulking factor as the main control factor. Based on this model, the air flow migration law of "roof-cutting and pressure-releasing" working face and open gob was studied, the air leakage area was found, and the air leakage prevention measures of setting up baffle, hanging wind tent, and shotcreting were put forward. The simulation and engineering verification showed that the measures were effective. At the same time, the distribution law of three zones of spontaneous combustion in gob after the implementation of air leakage prevention measures is analyzed, and the air leakage prevention measures can reduce the risk of coal spontaneous combustion. The research results provide an idea for air leakage control in the face of "roof-cutting and pressure-releasing" mining and contribute to the popularization of the technology of "roof-cutting and pressure-releasing".

The technology of "roof-cutting and pressure-releasing" is still in the developing stage, and it has some deficiencies, which need to be made perfect. In this study, we study the applicability of "roof-cutting and pressure-releasing" technology and "U" type ventilation and get some rules and findings. In the next step, we will consider the gas concentration distribution in the whole gob and the law of air flow and gas flow in the fissure zone and make more contribution to the popularization of the "roof-cutting and pressure-releasing" technology.

6. CONCLUSIONS

(1) Through the numerical simulation study, it is found that when no air leakage prevention measures are taken, the air leakage in the working face under "roof-cutting and pressure-releasing" mining is serious. The air flow provided by the intake airflow will flow directly into the gob-side entry retaining roadway. Along the working face inclination direction, the air volume is insufficient, and the normal air supply cannot be guaranteed. Along the direction of gob-side entry retaining, there is loss along the roadway. The air leakage law of the whole retaining roadway is "Sharply loss−Quickly loss−Slowly loss".

(2) In view of the air leakage in the mining face with "roof-cutting and pressure-releasing", three air leakage prevention measures are put forward, which can effectively prevent air leakage through simulation calculation. The baffle can effectively block the air flow into the retained entry; along the inclined direction of the working face, hanging the wind tent to ensure the normal ventilation of the working face, the serious air leakage area disappears and is replaced by the eddy current area of 0−30 m; shotcreting can effectively control the air leakage in gob-side entry retaining in the range of 80-480 m behind the working face, but the air leakage is still serious in the range of 0−80 m behind the working face because the gob is not completely collapsed.

(3) After taking measures to prevent air leakage, the range of cooling zone in gob is reduced from 0−190 to 0−50 m behind the working face, and the range of oxidation zone in gob is reduced from 190−320 to 50−105 m behind the working face, the range of asphyxiation zone in gob is expanded from 320−480 to 105−480 m behind the working face. The change law of the three zones shows that the air leakage prevention measures are effective, which can reduce the possibility of spontaneous combustion of residual coal in the goaf and ensure the safety and efficient production of the "roof-cutting and pressure-releasing" working face.

(4) Comparing the measured data with the simulated data after the same air leakage prevention measures, there is a slight error in the variation law of the airflow velocity in the inclined direction of the working face, and the variation law of the airflow velocity in the gob-side entry retaining is the same. As a whole, the simulation results can represent the law of air flow movement in the "roof-cutting and pressure-releasing" mining working face.

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Notes

The authors declare no competing financial interest.

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