Characteristics of Airflow Migration in Goafs under the Roof-Cutting and Pressure-Releasing Mode and the Traditional Longwall Mining Mode

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ABSTRACT: The airflow exchange between a mining face and a coal mine goaf can cause gas transfinite and spontaneous coal combustion disasters, threatening coal mining. Studying the characteristics of airflow movement in a goaf forms the basis to prevent airflow exchange for coal mining safety. Different from the traditional longwall mining mode, the roof-cutting and pressure-releasing mining mode shows new roof collapse characteristics and a ventilation system, which lead to obvious changes in the characteristics of airflow movements in coal mine goafs. To study the differences in airflow movement characteristics and the airflow disturbance influence area in a coal mine goaf between these two mining modes, the airflow movements in different goafs are compared using a numerical simulation method based on the measured parameters of the 1201 mining face in the Halagou Coal Mine, China. The results show that the airflow disturbance area in the goaf under the traditional longwall mining mode is a "η" type. Along the inclination direction of the mining face, two main exchange areas for the airflow are located in the 0−5 and 15−45 m sections, respectively. The airflow disturbance area in the goaf under the roof-cutting and pressure-releasing mining mode is a "hump" type, and there are six main exchange areas in the goaf under the roof-cutting and pressure-releasing mining mode. Along the inclination direction of the mining face, three exchange areas are located in the 0−25, 255−305, and 305−320 m sections, respectively. Along the strike direction, three exchange areas are located in the 5−25, 25−35, and 35−65 m sections, respectively. Based on the research results, sealing measures are taken to slow and eliminate airflow exchange in the goaf under the roof-cutting and pressure-releasing mining mode, and this provides theoretical guidance for safe coal mining.
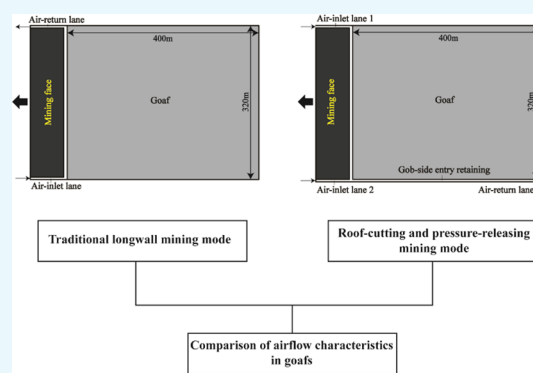
1. INTRODUCTION

Coal is the main source of energy in China, as well as an important basic energy and chemical raw material. In 2020, China's coal consumption accounted for 56.8% of the total energy consumption, with a year-on-year growth of 0.6% and an increase of 1.4% in the raw coal production.[1] Thus, coal plays a leading role in China's economic development. The safe production of coal mines has an extremely important impact on the sustainable development of the national economy and the lives and property of the people. Coal mining operations in China are mainly underground mining operations, with complex geological and production conditions and a wide variety of disasters. Among them, gas disasters and mine fires are the main disasters affecting coal mine safety,[2−5] and the airflow exchange between the mining face and goaf is the main reason for the occurrence of the two disasters. Most gas disasters in coal mines are caused by the accumulation and overruns of gas in the mining face. Because the mining face and goaf cannot be completely isolated, there is an airflow convergence channel, through which the airflow enters the

goaf, and the gas desorbed by the residual coal is brought to the upper corner of the mining face to form an airflow vortex. Under the gas-floating effect, the gas in the upper corner exceeds the limit. Mine fires are divided into internal and external fires according to the reasons of their occurrence.[6] The main cause of internal fires is that the oxygen brought by the airflow from the mining face into the goaf spontaneously combusts the coal left in the goaf.[7] Therefore, mastering the characteristics of airflow migration and the law of airflow exchange in the goaf forms the basis for safe production at the mining face.

At present, most traditional longwall mining modes in China need to excavate two roadways in one mining face, and coal
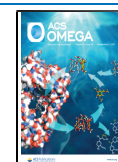
pillars need to be reserved to balance the pressure transmitted from the roof of the mining face. The resource recovery rate is reduced by 20−40% owing to the retaining coal pillars, resulting in a considerable coal resource wastage. Under the traditional longwall mining mode, the mining face is mostly a "U"-type ventilation system. The airflow enters the mining face from the air inlet roadway and then flows out through the air-return roadway. During this period, a part of the airflow enters the goaf, resulting in the gas being accumulated in the goaf gushing out from the upper part of the mining face after mass exchange with this part of the airflow, resulting in the concentration of disaster gas in the upper corner of the goaf exceeding the limit.[8] In addition, in this mining mode, at least two mining faces need to be tunneled in one mining face, which considerably increases the amount of long-wall mining roadway tunneling engineering and mining costs. To prepare a mining face, the roadway needs to be excavated for one to two years in advance. The amount of coal road excavation substantially affects the production efficiency of raw coal. With the depletion of shallow coal resources and the increasing depth of coal mining, safety issues, such as coal-mine-rock bursts, coal and gas outbursts, and large deformations of surrounding rocks, have become more prominent.[9,10] The traditional gob-side entry-retaining method involves filling a supporting wall at the side of the goaf.[11−13] Although no pillar mining is realized, the roadway is difficult to maintain. Recently, roof-cutting and pressure-releasing mining technologies have quietly emerged in the coal industry. This mining technology only needs to excavate a roadway or no roadway in one mining face, thereby reducing the amount of roadway excavation, achieving pillarless mining, and increasing the coal recovery rate. In addition, along the goaf edge, the energy-accumulated blasting technology[14] is used to cut the roof, which cuts off the stress transmission in the lateral direction and optimizes the stress distribution of the surrounding rock in the goaf.[15,16]

Under the traditional longwall mining mode, the roof cannot fully collapse because of the support of the coal pillars in the goaf area, and the coal pillar-influenced areas are formed on both sides of the coal pillars.[17] The porosity and permeability in this area are relatively large. In the roof-cutting and pressure-releasing mining mode, there is no support on the goaf side to support the roof, and thus, the goaf roof can completely collapse, resulting in changes in the permeability characteristics of the goaf. Compared with the traditional longwall mining mode, the roof-cutting and pressure-releasing mining mode has evident differences in the layout of the mining face and its ventilation system. Therefore, there must be differences in airflow movement under the two different mining modes.

Extensive research has been conducted on airflow movement in the goaf under the traditional longwall mining mode. Under laboratory conditions, because the porosity distribution in the goaf is highly complicated, it is difficult to perform a reasonable and accurate physical simulation of the airflow field in the goaf. The computational fluid dynamics (CFD) software can be used for a relatively accurate flow-field numerical simulation.[18,19] Gao et al.[20] used the Fluent software to simulate the airflow field and gas-distribution law in the goaf under the "U"-type ventilation mode. The simulation results showed that part of the airflow leaking into the goaf flows from the return air side to the mining face, whereas part flows to the deep part of the goaf and converges with the gas emitted from the deep part. Li et al.[21] used simulation software to simulate the 3D-

space gas-floating characteristics of the goaf behind the mining face. The results showed that the relation between the high-level drainage flow and the gas volume fraction is approximately an inversely proportional function, and that between the high-level drainage flow and gas volume fraction of the air return lane is a negative exponential function. Wang et al.[22] used PFC3D to simulate the collapse of overlying strata, extracted the quantitative porosity data of the goaf, input them into the Fluent software to simulate the airflow field of the goaf, and verified it with the actual situation. Gao et al.[23] used the method of numerical simulations to obtain the gas concentration distribution law in the goaf of the mine, solved the problem of gas transfinite in the upper corner of the mining face, and optimized the nitrogen injection parameters. Shi et al.[24] established a CFD model of coal spontaneous combustion under the conditions of gas drainage in the goaf, and numerically simulated the oxygen distribution in the goaf of a fully mechanized mining face. According to the simulation results, the spontaneous combustion zone area of the goaf is obtained, which provides a basis for formulating mine fire prevention measures. However, the characteristics of airflow migration in the goaf under the roof-cutting and pressure-releasing mining mode have been rarely studied. Chen et al.[25] studied the evolution law of porosity and permeability of the goaf under this mode by analyzing the movement law and lateral stress change of the overlying strata in the goaf. Liu.[26] studied the evolution law of goaf permeability under the "Z"-type ventilation system of roof-cutting and pressure-releasing roadway and simulated the influence of mining-face air distribution on goaf airflow migration by using the Fluent software. So far, the law of airflow exchange in the goaf under the traditional longwall mining mode has been extensively studied; however, the law of airflow exchange in the goaf under the roof-cutting and pressure-releasing mining mode has been rarely studied and there is no comparative study on the law of airflow migration in the goaf under these two mining modes.

Therefore, this study analyzes the mining-face layout, mining technology, and ventilation system of the traditional longwall mining mode and the roof-cutting and pressure-releasing mining mode. According to the different evolution laws of goaf permeability, the airflow migration characteristics of the goaf under the two different mining modes are simulated using numerical simulation software and their differences are compared. The research results are significant for preventing airflow exchange between the mining face and goaf and the promotion and protection of roof-cutting and pressure-releasing technology for safe mining.

2. FIELD SECTION

2.1. Roof-Cutting and Pressure-Releasing Mining Mode. The roof-cutting and pressure-releasing mining mode is based on the theory of "roof-cutting short-arm beam" proposed by Academician He.[27] When mining a mining face, only one roadway along the channel needs to be dug and the other roadway along the channel is automatically formed; moreover, there is no need to leave the coal pillars. Under this mode, first, the gob-side entry is excavated and exited while retaining the mining face and the lower mining face. After the shearer cuts the roof of the roadway space, a constant-resistance and large-deformation anchor cable[28,29] is used to strengthen the roadway support. In addition, at the advanced mining face, the roof is precracked along the trough direction by the directional energy-accumulation blasting technol-
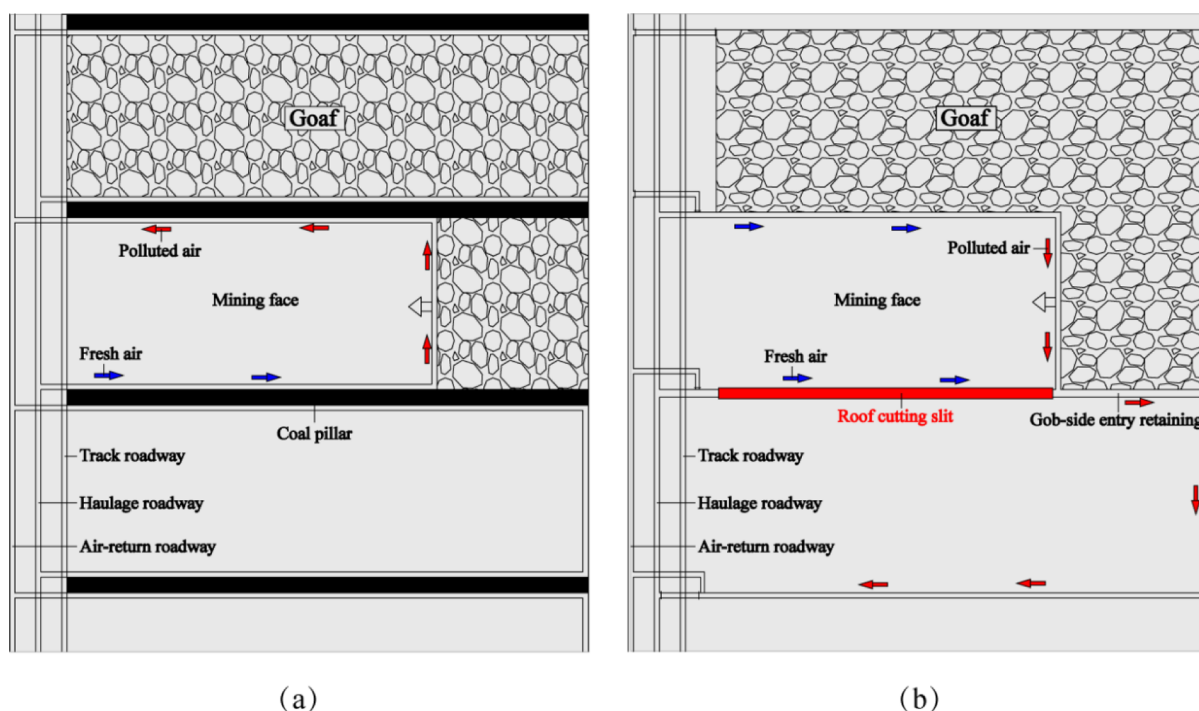
Figure 1. Comparison of mining-plane layout. (a) Traditional longwall mining mode; (b) roof-cutting and pressure-releasing mode.

ogy,[30−32] which cuts off the stress transfer between the roadway and goaf roof and forms a presplit cutting seam surface along the roof of the goaf side of the gob-side entry retaining. The roof of the roadway forms a "cut-top short-arm beam structure." After the mining face, the roof of the goaf behind the support collapses on its own along the cut-seam surface and forms a roadside, and then, the temporary support after the erection and the support of the roadside gangue are performed. When the surrounding rock deformation of the gob-side entry retaining stabilizes, the temporary support is removed after the frame is removed, thereby forming a channel along the mining face, which is used as a mining roadway in the adjacent mining face to serve the mining of the next mining face. Under this mining mode, the mining face adopts a "Y"-type ventilation system, which includes two air inlet roadways and one air-return roadway. Among them, one is the main-air inlet lane and the other is the auxiliary-air inlet lane. One laneway set up by the gob-side entry retaining technology along the goaf is used as the air-return lane behind the mining face, and the three lanes together form the ventilation system of the mining-face goaf. Figure 1 compares the mining-plane layout between the traditional longwall mining mode and the roof-cutting and pressure-releasing mining mode.

2.2. Difference between the Traditional Longwall Mining Mode and the Roof-Cutting and Pressure-Releasing Mode. The roof-cutting and pressure-releasing mining mode has the following differences from the traditional longwall mining mode. (1) One mining face is reduced from the original two tunneling roadways to one. (2) It is no longer necessary to leave the coal pillars in the goaf area of the next mining face, eliminating the area affected by the coal pillar support. (3) The stress transfer of the surrounding rock roof of the goaf is transformed from the original "voussoir beam"[33] or "transmission rock beam"[34] into a "roof-cutting short-arm beam," which optimizes the pressure distribution of the roof's surrounding rock. (4) The ventilation system of the mining

face is changed from the traditional "U" type to "Y" type, and the problem of overlimit gas in the upper corner is effectively addressed.

2.3. Overview of the Experimental Mine. The experimental mine used in this study is the Halagou Coal Mine of the China Shenhua Shendong Coal Company. It is located on the east side of the Wulanmulun River, 55 km northwest of Shenmu County, Shaanxi Province, and is under the jurisdiction of Daliuta Town. The mine field area is 85 km² and the approved production capacity is 16 million tons/year. There are eight mineable and partially mineable coal seams. The main coal seams are 2-2, 3-1, and 4-2 coal, all of which are near-level coal seams. The stratum in this area is generally in a monoclinic structure inclined toward the southwest direction, with little undulations, but broad and gentle undulations, with dip angles of generally less than 1°. There is a small-scale normal fault in the south of the mine, without magmatic rock intrusion, and the overall structure is simple. The mine is identified as a gas mine. The coal seam tends to spontaneously combust. The fire period lasts for approximately 1 month. It is a type I spontaneous coal seam. A large stacking volume and a long stacking period can cause spontaneous combustion.

The 1201 fully mechanized mining face of the Halagou Coal Mine is the top-cutting pressure relief experimental mining face, and the 12201 fully mechanized face is the first mining face in the second panel of the 12th coal mine. The thickness of the coal seam is 0.8−2.2 m and the average coal thickness is 1.92 m. The coal volume is 610,000 tons, the coal seam is relatively stable, and the designed 12202 mining face is northwest.

The overlying bedrock on the 12201 mining face is 55−70 m thick, the loose layer is 0−33.48 m thick, and the buried depth is 60−100 m. The bedrock is exposed on the surface of the area near the retreat channel. The direct roof of the coal seam is siltstone with a thickness of 3.9−0.52 m and an average thickness of 1.84 m; the upper part of the direct roof is a 12-up

coal seam of various thicknesses, with a thickness of 0.0−2.75 m and an average thickness of 1.56 m; the upper 12th coal seam is mudstone with a thickness of 2.14−0.55 m and an average thickness of 1.35 m; the old roof is composed of fine-grained sandstone with an average thickness of 3.34 m and siltstone with an average thickness of 4.05 m; and the direct bottom is siltstone with an average thickness of 3.67 m.

The length of the 12201 mining face is 320 m, that from the cut to stopline is 747 m, and that of the gob-side entry retaining is 580 m. The traditional longwall mining mode is adopted from the open-off cut to the open-off cut 12202 in the mining face. After the mining face is pushed through the open-off cut 12202 in the mining face, the roof-cutting and pressure-releasing mining mode is used instead. The layout of the mining face is shown in Figure 2. The goaf of the traditional
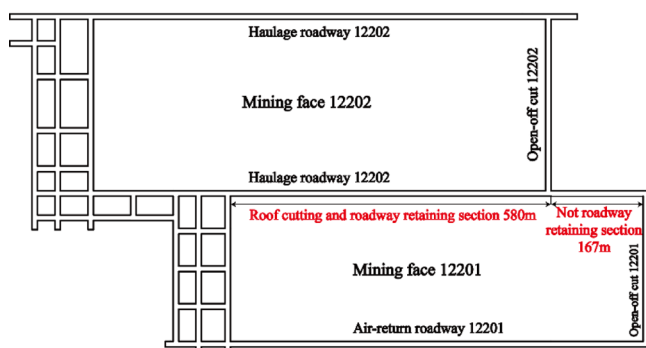

Figure 2. Mining face layout of Halagou Coal Mine.

longwall mining mode is 167 m long and adopts the "U"-type ventilation method; that is, fresh airflow enters from the air-return roadway 12201, flows through the mining face, then enters haulage roadway 12201, and flows out through open-off cut 12202. The mining face of the roof-cutting and pressure-releasing mining area is 580 m long, and the ventilation system is changed to the "Y" type; that is, the 12201 air-return roadway and the haulage roadway 12201 are both air-inlet roadways. The airflow in the 12201 air-return roadway merges with that in the haulage roadway 12201 after it passes through the mining face. Next, the confluent airflow continues to flow along the haulage roadway 12201 and then flows out through the open-off cut 12202.

3. THEORETICAL ANALYSIS

When studying the laws of airflow movement in the goaf, the goaf is regarded as a porous-medium area composed of collapsed rock mass and remnant coal,[35] and its permeability is an important factor affecting the simulation results of the airflow field. Different mining modes exhibit different roof collapse characteristics in the goaf, which leads to different permeability characteristics in the goaf.[36,37]

3.1. Roof Collapse Characteristics of the Traditional Longwall Mining Mode. Under the traditional longwall mining mode, with the continuous advancement of the mining face, the goaf roof collapses under the action of periodic pressure. Under the influence of its own weight and mining, the overlying rock layer in the goaf produces bending deformation, fracture, and separation of layers. The roof collapse is divided into three stages according to the advancement of the mining face: the initial collapse phase, periodic collapse phase, and compaction stable phase. The

mining face of the traditional longwall mining mode advances from an open cut. As the mined area gradually increases, the immediate roof collapses first with coal mining work. When the roof reaches the limit span, the immediate roof collapses in a large area under the action of its own weight and the load of the overlying rock layer and assumes a natural accumulation state. This period is called the initial collapse phase, during which the collapsed gangue is compressed under its own weight. With the continuous advancement of the mining face, the basic roof bending moment continues to increase, and when it reaches its strength limit, fracture occurs for the first time. The rotation and sinking of the basic roof load the gangue that has collapsed in the goaf and compress the broken gangue after touching it. Later, the goaf roof periodically collapses with the advancement of the mining face. This period is called the periodic collapse stage. In the later stage of mining, the basic roof rotation movement tends to be stable and the falling gangue is slowly compressed under the action of its own weight and the overlying load, until it sinks and stabilizes, and the broken gangue is compacted. This period is called the stable compaction stage.

The collapse model of the goaf under the traditional longwall mining mode is shown in Figure 3. Here, in the
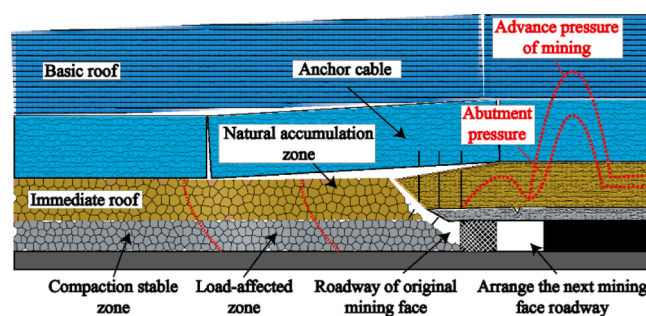

Figure 3. Roof collapse of goaf in the traditional longwall mining mode.

traditional longwall mining method based on the theories of "voussoir beam" and "transmission rock beam" during the mining process of the mining face, the roof of the roadway produces separation and a large deformation failure by the pressure generated by periodic breaking. After mining, the original mining face roadway is destroyed, the anchor cable is broken, and two stress peak areas of abutment pressure and mining advance pressure are produced near the next mining face roadway. Finally, the coal pillars are left to support the roof and avoid the influence of the concentrated stress areas on the stability of the surrounding rock of the roadway. The roof is supported by the "reinforced anchor rod + anchor cable + lead wire mesh" for joint support. The porosity is not constant in the goaf, and a natural accumulation zone, load-affected zone, and compaction stable zone are formed in the horizontal direction.[38] The porosity of the goaf is larger on the side close to the mining face. The farther away the goaf is from the mining face, the smaller is the porosity of the goaf.

3.2. Evolution of Goaf Permeability under the Traditional Longwall Mining Mode. The porosity and permeability of the goaf are important parameters that affect the numerical simulations of the flow field in the goaf. The permeability of the goaf is determined by the pores formed by coal and rock accumulation in the goaf. The greater the porosity of the coal and rock in the goaf, the stronger is the

airflow capacity. The porosity of the goaf is stable in the compaction stability zone and related to the breaking expansion coefficient of the rock in the goaf,[39] and can be expressed as

$$n = 1 - \frac{1}{K_p} \qquad (1)$$

where n is the porosity of the goaf (dimensionless) and K_p is represents the coefficient of expansion of the rock mass (dimensionless).

The goaf is regarded as a porous medium and the gas flow mode is porous-medium seepage. Many scholars have regarded Darcy's law as the laminar flow law of porous media and used macroscopic hydrodynamic theories and methods to study the relations among the permeability, porosity, and particle size of the granular media packed bed.[40] According to the Blake−Kozeny equation,[41,42] the relation can be obtained as

$$\Delta k = \frac{D_p^2 n^3}{150(1 - n^2)} \qquad (2)$$

where k is the permeability of the goaf (m^2) and D_p is the average particle diameter (m).

3.3. Roof Collapse Characteristics of the Roof-Cutting and Pressure-Releasing Mining Mode. Before mining, the two-way energy-accumulating blasting method is used to directionally cut the roof rock layer of the roadway. The roadway-surrounding rock deformation characteristics are divided into three stages: the pressure-releasing period, dynamic pressure deformation period, and compaction stable period. After the mining face is mined, as the support moves forward, the immediate roof of the cutting area loses support, and under the influence of its own weight and mining, it breaks into an inverted cantilever beam state. This process is called the pressure-releasing period because the swelling of the rock gradually fills the goaf. At this time, the gangue in the goaf is in a self-stable state that is not completely filled and does not support the overlying rock. With the continuous progress of the mining face, when the immediate roof is completely collapsed, the basic roof also fractures, rotates, and sinks under the action of periodic pressure and continues to compact the gangue that has collapsed in the goaf. The roof rock layer gradually stabilizes under the effective support of the gangue. This period is called the dynamic pressure-deformation period. At this time, the gangue packing density of the goaf is further improved and the goaf is completely filled. When the mining face advances to a certain distance, the gangue in the goaf is completely compacted and the overlying rock layer is effectively supported. The basic roof rock layer tends to stabilize and no longer sinks, forming a stable voussoir beam structure. This period is called the compaction stabilization period. At this time, the single pillars of the retaining section can be gradually removed and only the gangue-retaining structure can be retained. Because of the presplitting blasting of the roadway roof before mining, the connection and stress transfer between the roadway and goaf roof are cut off and the goaf roof completely collapses. The goaf is filled in time and supports the overlying roof slab, thereby reducing the subsidence and deformation of the overlying roof slab.

The collapse model of the goaf in the roof-cutting and pressure-releasing mining mode is shown in Figure 4. Under this mining mode, the roof is formed into a short arm beam by the energy-accumulating slitting technology, which cuts off the
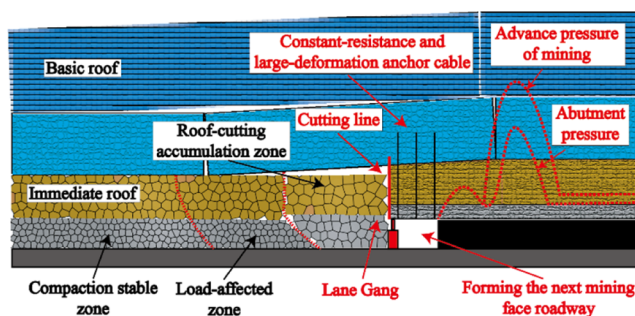

Figure 4. Roof collapse in the goaf of the roof-cutting and pressure-releasing mining mode.

stress transmission of the roof. After the mining face is mined, the roof automatically collapses along the cutting line to form the roadway of the next mining face. The high-resistance anchor cable can provide sufficient rigidity, strength, and deformation without being damaged. In addition, the supporting pressure of the roof and the advance pressure of mining move backward, effectively reducing the threat of the high-stress environment of the roof in the goaf area. The goaf forms a roof-cutting accumulation area, a load-affected area, and a compaction stable area in the horizontal direction. The porosity is the largest in the roof-cutting accumulation zone, and the porosity is the smallest in the compaction stable zone.

3.4. Evolution of Goaf Permeability under the Roof-Cutting and Pressure-Releasing Mode. In the roof-cutting and pressure-releasing mining mode, the permeability changes owing to the change in the roof collapse characteristics of the goaf. Du introduced the concept of the filling degree in the following formula.[25] In the pressure-relief stage, the main process is the collapse of the roof rock mass in the goaf. At this time, because part of the goaf roof is in a suspended state, the collapsed rock mass has not completely collapsed; moreover, it has not played a supporting role and is in a free and loose state. Therefore, at this time, the porosity of the goaf is mainly related to the breaking expansion coefficient, and the relation can be expressed as

$$N = 1 - \frac{1}{K_p}\eta \qquad (3)$$

where N is the porosity of the goaf (dimensionless); K_p is represents the coefficient of expansion of the rock mass (dimensionless); and η is the filling degree, and it takes a value between 0 and 1 (dimensionless).

When $\eta = 0$, the rock mass has not yet collapsed, and the void ratio of the goaf is 1; when $\eta = 1$, the rock mass has fully collapsed. At this time, the porosity of the goaf is only related to the breaking expansion coefficient of the rock block. The filling degree increases with the distance of the lagging mining face. Here, the distance between the filling degree and the lagging mining face is regarded as a linear relationship, and the expression of the filling degree and the distance between the lagging mining face is obtained as

$$\eta = \frac{L}{L_0} \qquad (4)$$

where L is the distance of lagging mining face (m) and L_0 is the advancing distance of the mining face when the roof of the goaf fully collapses (m).
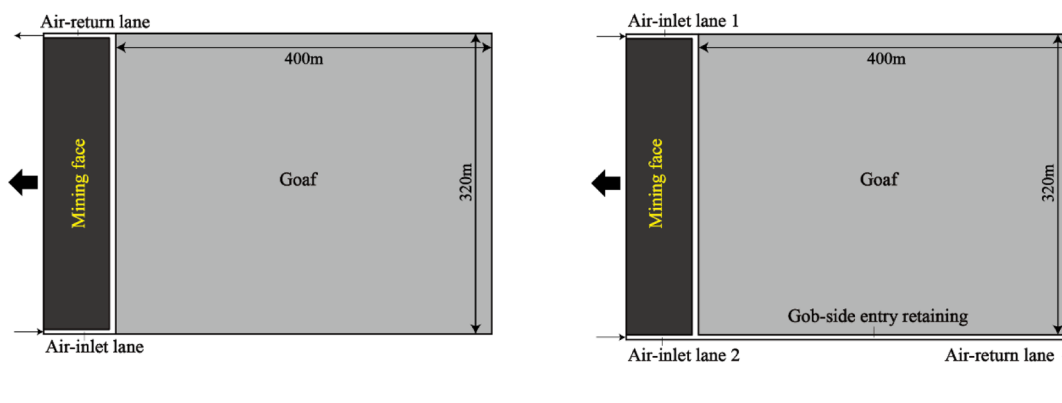
Figure 5. Physical model of goaf.

Therefore, the study on the permeability distribution of the goaf under the roof-cutting and pressure-releasing mining mode is divided into a fully collapsed stage and an insufficiently collapsed stage. When the goaf is not completely collapsed, K_p takes the maximum value K_{pmax} and the permeability of the goaf at this time can be expressed as

$$K' = \frac{D_p^2}{150} \times \frac{\left(1 - \frac{L}{K_{pmax}L_0}\right)^3}{\left(\frac{L}{K_{pmax}L_0}\right)^2} \tag{5}$$

When the goaf is fully collapsed, $\eta = 1$, then eq 5 can be simplified as

$$K' = \frac{D_p^2}{150} \times K_p^2\left(1 - \frac{1}{K_p}\right)^3 \tag{6}$$

4. RESULTS

Fluent software is a widely used commercial CFD software platform recognized at home and abroad. It is essentially a solver based on the finite-volume method. Users can obtain intuitive solutions by establishing models, performing flexible meshing, compiling the UDF, choosing reasonable solution methods, and data postprocessing to improve the efficiency of calculations. As long as it can be used in industries related to fluids, heat transfer, and chemical reactions, and is widely used in aerospace, automotive design, oil and gas, and turbine design, this paper uses Fluent software for numerical simulations.

4.1. Basic Governing Equations of Flow Field in Goaf. Because the goaf is regarded as a continuous heterogeneous porous-medium space, the gas flow in the goaf follows the law of conservation of mass, energy, and momentum. The governing equations are mathematical descriptions of these conservation laws and are combined with specific boundary conditions and initial conditions to form a mathematical model of the airflow in the goaf.

The mass conservation equation is also called the continuity equation, applicable to any form of fluid flow, and it can be expressed as

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho v_g) = 0 \tag{7}$$

where ρ is the gas density (kg/m³); v_g is the gas flow rate (m/s); and t is the time (s).

The law of conservation of energy is the basic law to be followed in the flow system, and it can be expressed as

$$\frac{\partial(\rho T)}{\partial t} + \text{div}(\rho U T) = \text{div}\left(\frac{k}{c_p}\text{grad}(T)\right) + S_T \tag{8}$$

where c_p is the specific heat capacity (J/(kg·K)); T is temperature (K); k is the heat transfer coefficient of the fluid (dimensionless); and S_T is the viscous dissipation term (dimensionless).

The momentum conservation equation is also called the Navier−Stokes equation (abbreviated as the N−S equation), and it can be expressed as

$$\rho\left(\frac{\partial vg}{\partial t} + (vg \cdot \nabla)vg\right) = -\nabla P + \rho g + \nabla \cdot \tau + S \tag{9}$$

where P is the static pressure on the infinitesimal body (Pa); g is the acceleration of gravity (m/s²); and τ is the viscous stress tensor.

The additional resistance of porous media to the airflow in the goaf is simulated by adding the momentum loss source term S_i to the momentum equation. The momentum loss source term consists of two parts: a viscous loss term and an inertial loss term. Its basic form can be expressed as

$$S_i = \sum_{j=1}^{3} D_{ij}\mu v_j + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho|v_j|v_j \tag{10}$$

where S_i is the momentum loss source of porous media (dimensionless); μ is the dynamic viscosity (Pa·s); and v_j ($j = 1$, 2, and 3) is the velocity component in the x, y, and z direction (m/s); ρ is the fluid density (kg/m³); D_{ij} is the coefficient of viscous resistance (dimensionless); and C_{ij} is the coefficient of inertial resistance (dimensionless).

4.2. Model Establishment and Boundary Condition Setting. In the process of model building, appropriate simplifications and assumptions should be made to the model according to the content and purpose of the simulation. In actual mine production, owing to the complex environment of the goaf, to facilitate the study of the characteristics of airflow migration, the following assumptions are made:

(1) The goaf is regarded as an isotropic porous medium. In the numerical simulation, the mining face, air inlet and return roadway, and goaf are all regarded as rectangles.

(2) The gas in the goaf is an incompressible ideal gas, and the gas flow process is in a steady state. The influence of factors such as gas emission and temperature on the goaf airflow is ignored.

(3) Owing to the simple geological structure within the test mining face and the small inclination of the coal seam, the goaf is treated as horizontal.

(4) The airflow in the air-inlet and return roadway and the mining face area is set as the turbulent flow, whereas that in the goaf area is set as laminar flow.

4.2.1. Model Building. According to the actual situation of the 1201 fully mechanized mining face in the Halagou Coal Mine, to compare the differences between the two, the length of the goaf model under the traditional longwall mining mode and the roof-cutting and pressure-releasing mining mode is 400 m and the inclination length is 320 m. The cross section of the roadway is rectangular with a width of 5 m. The model is divided into tetrahedral grids. The traditional longwall mining mode and the roof-cutting and pressure-releasing mining mode are divided into 362,031 and 454,027 grids, respectively. The establishment of a numerical simulation model for air leakage in the goaf is shown in Figure 5, and the basic parameters of the model are listed in Table 1. Among them, the porosity in

Table 1. Basic Parameters of the Model

category	traditional longwall mining mode	roof-cutting and pressure-releasing mining mode
length of mining face	320 m	320 m
strike length	400 m	400 m
ventilation method	U type	Y type
inlet boundary	1.5 m/s	air return lane 1: 1.0 m/s
		air return lane 2: 0.5 m/s
outlet boundary	outflow	outflow
walls around the goaf	no-slip boundary condition	no-slip boundary condition
hydraulic diameter	3.3333	air-return lane 1: 3.3333
		air-return lane 2: 3.3333
turbulence intensity	3.2586	air-return lane 1: 3.4288
		air-return lane 2: 3.7383
goaf setting	porous media area	porous media area
porosity, permeability, and viscous resistance coefficient	UDF	UDF

UDF compilation uses the formulas 1 and 3, the permeability formula uses the formulas 5 and 6, and the viscous resistance coefficient is the reciprocal of permeability.

4.2.2. Boundary Condition Setting. The physical model selects the standard $k-\varepsilon$ turbulence model, the airflow inlet boundary is set as the velocity inlet boundary condition, and the airflow outlet boundary is set as the free outflow. The boundary between the roadway and goaf is set as an internal boundary, the fluid can flow freely, and the remaining unset boundaries are the default solid-wall boundaries. All walls are under non-slip boundary conditions. The near wall of the mining face is treated using the standard wall function method and is insulated. Parameters such as the goaf-filling degree, breaking expansion coefficient, permeability, and average particle diameter are compiled into the UDF and loaded into the Fluent solver to obtain the goaf porosity and viscous resistance coefficient.

4.3. Characteristics of Airflow Migration in the Goaf of Traditional Longwall Mining Face. The total caving method is used as the roof management method of the goaf in the 1201 mining face of the Haragou coal mine. The airflow on the mining face and that close to the goaf penetrate the goaf and merge with it under the applied pressure difference. The pressure distribution in the goaf determines the airflow in the goaf. Figure 6a shows the pressure distribution in the goaf under the traditional longwall mining mode. Here, the pressure at the inlet of the air-inlet lane is greater than that at the outlet of the air-return lane, and the airflow pressure is the highest at the lower corner and smallest at the upper corner. The airflow pressure in the goaf gradually decreases from the entrance of the air-inlet lane to the goaf depth to no longer change and then gradually decreases from the middle of the goaf to the exit of the air-return lane. At the same time, the pressure gradient at both ends near the mining face is the largest. Figure 6c shows the velocity distribution of the mining face and goaf. Here, the airflow speed is the highest near the air-inlet and return lanes and very small in the goaf; moreover, only a small part of the airflows into the goaf.

The airflow line diagram of the goaf can intuitively reflect the path and direction of the airflow along the mining face to the goaf. The airflow streamline distribution of the goaf under the traditional longwall mining mode is shown in Figure 6b. Here, the airflow in the goaf is distributed in a "⊃" type and is symmetrical along the inclination direction of the mining face. Most of the airflow enters the goaf from the air-inlet lane of the mining face and a small part of the airflow flows through the mining face. The passage merges into the goaf in the middle of the mining face, and the two parts of the airflow flow out together from the air-return lane and upper corner. At the same time, the airflow velocity at the air-inlet and return lanes is the largest and gradually decreases along the goaf depth. A part of the flow lines is concentrated at the entrance of the air inlet and return lanes. The flow lines directly pass through the goaf, and the airflow in the middle of the mining face is correspondingly reduced.

The volume flow rate in the surface integrals of the Fluent software postprocessing function can be used to calculate the air volume exchange along the inclined direction of the mining face. Figure 7a shows the division of the mining face under the traditional longwall mining mode, and Figure 7b shows that of the air volume exchange along the mining face. The figures indicate air flowing into or out of the goaf from the entire mining face. The 0−5, 5−15, and 315−320 m sections along the inclination direction of the mining face are the areas, where airflows from the mining face to the goaf. The 15−45 and 45−315 m sections along the inclination direction of the mining face are the areas, where the airflow escapes from the goaf to the mining face. The total airflow from the mining face into the goaf is 133.06 m³/min, accounting for 11.83% of the total air distribution, and the inflow air volume in the 0−5 m area along the inclination direction of the mining face is 114.00 m³/min, accounting for 85.68% of the total inflow airflow, which is the main area into which the air flows. This is because the area is at the lower corner of the goaf, the airflow is almost perpendicular to the goaf along the air-inlet lane, and the airflow speed value reaches its maximum. As the air flows through the mining face, the airflow speed leaking to the goaf gradually decreases and the inflow air volume in the 5−15 m area is 12.11 m³/min, accounting for 9.10% of the total inflow air volume. The incoming-air volume in the 315−320 m area is
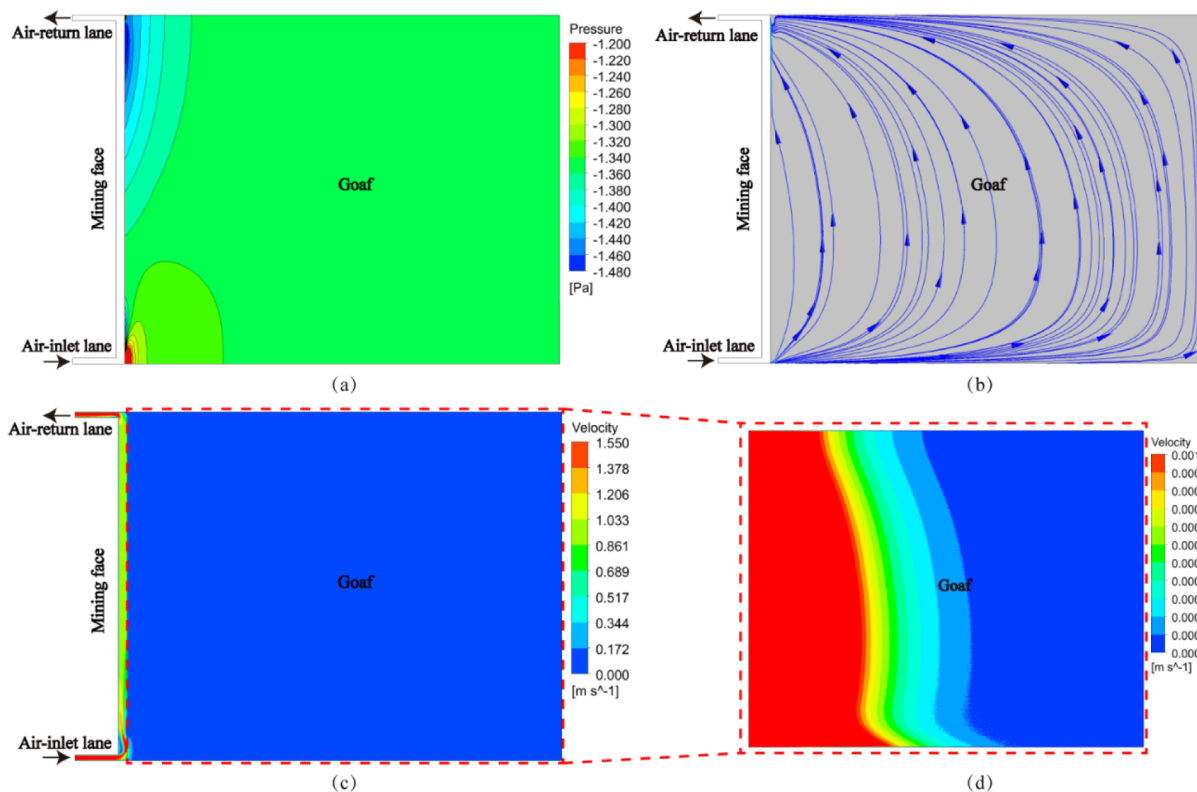
Figure 6. Traditional longwall mining mode. (a) Pressure distribution in the goaf; (b) streamline distribution in the goaf; (c) velocity distribution; and (d) velocity distribution in the goaf.
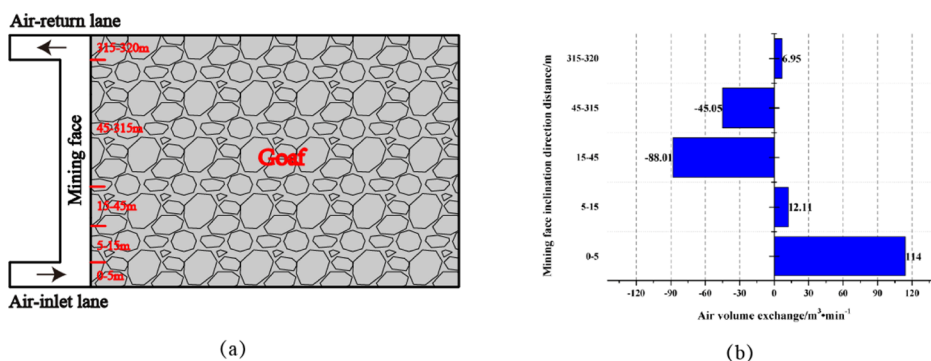

Figure 7. (a) Division of the mining face; (b) distribution map of air volume exchange along the mining face.

6.95 m³/min, accounting for 5.22% of the total incoming-air volume. This section is located near the air-return lane, and the phenomenon of air flowing from the mining face into the goaf is attributed to the vortex generated near the corner of the mining face. In the 15−45 m section, the amount of air escaping from the goaf to the mining face is 88.01 m³/min, accounting for 66.14% of the total amount of escaping, and it is the main air-escaping area. In the 45−315 m section, the air volume escaped is 45.05 m³/min, accounting for 33.86% of the total air escape. This area has a wide range and a stable airflow exchange area.

The disaster in the goaf is caused by the airflow current that flows during the airflow exchange between the mining face and goaf, which creates a certain degree of the disturbing effect on the goaf. In addition, the probability of disasters in the goaf with a small degree of disturbance is small and areas with a large degree of disturbance are prone to disasters, as the leftover coal in the goaf will oxidize with oxygen exchanged

with the airflow and release heat. When heat cannot be dissipated and accumulated to a certain extent, there is danger. An airflow speed of less than 0.00167 m/s[43,44] cannot provide enough oxygen for the goaf; it is difficult for the remaining coal to oxidize and accumulate heat and the airflow has no disturbing effect in this area. Therefore, we use an airflow speed of 0.00167 m/s as the boundary and define the area where the airflow speed in the goaf is greater than 0.00167 m/s as the airflow disturbance area in the goaf and that where the airflow speed is less than 0.00167 m/s as the undisturbed area.

Figure 8 shows the airflow disturbance area in the goaf under the traditional longwall mining mode, according to the simulation results. Here, the airflow disturbance pattern in the goaf is a "η" type. The airflow disturbance depth in the goaf area near the air-inlet lane is the largest at a distance of 106 m and that near the air-return lane is the smallest at a distance of 45 m. The range of airflow disturbance in the goaf under the traditional longwall mining mode is determined as 0−106 m.
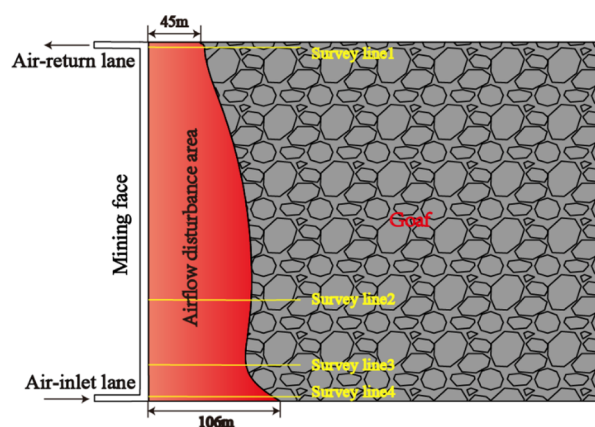
Figure 8. Airflow disturbance area in a goaf under the traditional longwall mining mode.

To describe the degree of airflow disturbance in the goaf, four velocity survey lines are arranged according to the disturbance pattern of the goaf, each of which is 120 m long. Survey line 1 is 3 m away from the air-return lane, survey line 2 is 100 m away from the air-inlet lane, survey line 3 is 30 m away from the air-inlet lane, and survey line 4 is 3 m away from the air-inlet lane.

The velocity distribution data along the goaf strike are obtained by monitoring the four survey lines, and the data within the range of 30−120 m are intercepted and plotted into the velocity point line in Figure 9. Here, the airflow speed is
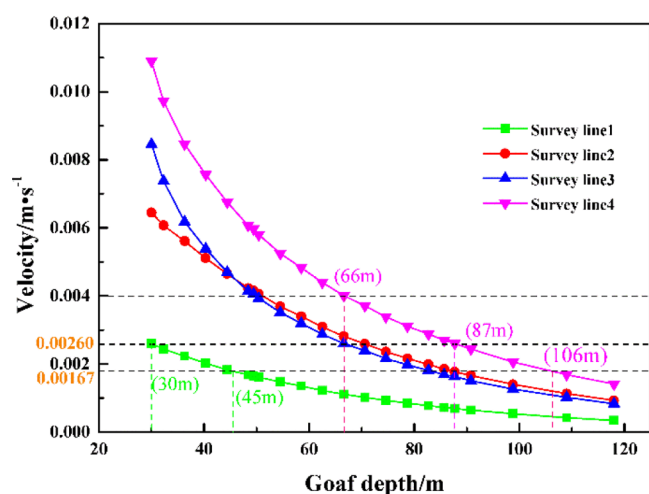

Figure 9. Airflow velocity distribution along the strike direction of a goaf.

higher in the goaf area closer to the mining face and gradually decreases along the direction of the goaf area. Viewed from the direction of the inclination of the mining face, the airflow speeds at all positions along the strike direction in the goaf near the air-inlet lane are higher than those in the middle of the goaf and on the inlet side, and the airflow speed at 30 m near the air-inlet lane is greater than that 100 m away from the air-inlet lane at approximately 50 m depth in the goaf, and vice versa after 50 m. The degree of airflow disturbance in the goaf disturbance area is classified according to the survey line data. The range of airflow speed exceeding 0.00400 m/s is defined as the area of moderate airflow disturbance, the range within 0.00400−0.00260 m/s is the area of severe airflow disturbance,

the range within 0.00260−0.00167 m/s is the area of slight airflow disturbance, and that less than 0.00167 m/s is the area of undisturbed airflow.

The distribution diagram of the degree of airflow disturbance in the goaf can be obtained from the velocity distribution shown in Figure 10. According to Figures 9 and 10, along the strike direction of the goaf, the range of area of moderate airflow disturbance near the inlet side is 0−66 m and that near the return-air side is between 0 and 6 m. The airflow speed in the goaf is relatively high in areas with moderate airflow disturbance. The airflow from the mining face into the goaf can bring enough oxygen and remove the heat generated by the oxidation of the leftover coal. Thus, the heat cannot accumulate and the spontaneous combustion of coal does not occur. However, higher airflow speeds may carry most of the gas to the upper corner of the goaf, causing gas accumulation and leading to a gas disaster. The area of severe airflow disturbance near the inlet side is 66−87 m and that near the return side is 6−30 m. In areas where the airflow is severely disturbed, the airflow speed in the goaf can provide enough oxygen for the oxidation reaction of the leftover coal. The oxidation reaction completely releases heat and the airflow speed cannot remove the accumulated heat; therefore, spontaneous combustion is prone to occur. At the same time, it drives part of the gas in the goaf to flow to the vicinity of the air-return lane, causing the gas to exceed the limit. Therefore, this area is the most dangerous. The area of slight airflow disturbance near the inlet side is 87−106 m and that near the return side is 30−45 m. The airflow speed in this area is relatively small, which causes a small amount of oxygen to slowly oxidize with the remaining coal and a gradual heat accumulation. In addition, spontaneous coal combustion might occur; however, it is relatively small. After 106 m from the inlet side and 45 m from the return side, the airflow area is undisturbed. In this area, the goaf is not affected by airflow, resulting in disasters.

4.4. Characteristics of Airflow Migration in Goaf of the Roof-Cutting and Pressure-Releasing Mining Mode. Figure 11a shows the pressure distribution in the goaf under the roof-cutting and pressure-releasing mining mode, where the pressure cloud map of the goaf is approximately slanted and symmetrically distributed. The airflow pressure gradually increases along the inclination direction of the mining face and is the largest at one corner of the air-inlet lane, whereas the airflow pressure gradually decreases along the goaf direction and is the smallest at the air-return lane.

The streamline distribution in Figure 11b and the velocity distribution in Figure 11c indicate that the airflow in the goaf is distributed in a "1/4 arc" type under the roof-cutting and pressure-releasing mining mode. The airflow velocity attenuates significantly along the goaf direction. In the deep part of the goaf, the airflow velocity is very small or even zero. The airflow entering from air-inlet lane 1 produces a larger vortex area in the corner of the air-inlet lane 1 inside the goaf. This is mainly because the inlet airflow passes through the turning point during the process of flowing into the mining face from air-inlet lane 1, and the fluid fulcrum is subjected to centrifugal action, thereby forming a deceleration and pressurization area on the outside. The airflow velocity is relatively high and most of the air flows into the goaf from this area. Part of the airflow that enters the goaf flows in the direction of the gob-side entry retaining, and remaining the part returns to the mining face and flows in the direction of the inclination of the mining face.
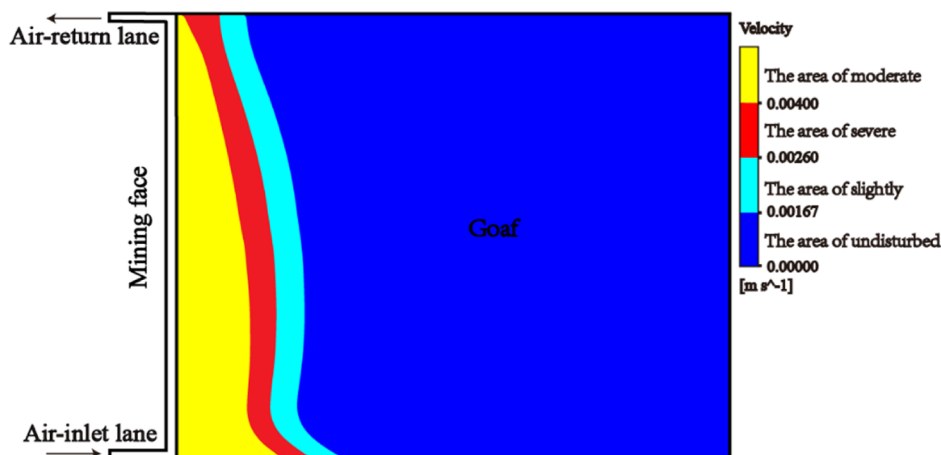
Figure 10. Distribution of the degree of airflow disturbance in the goaf under the traditional longwall mining mode.
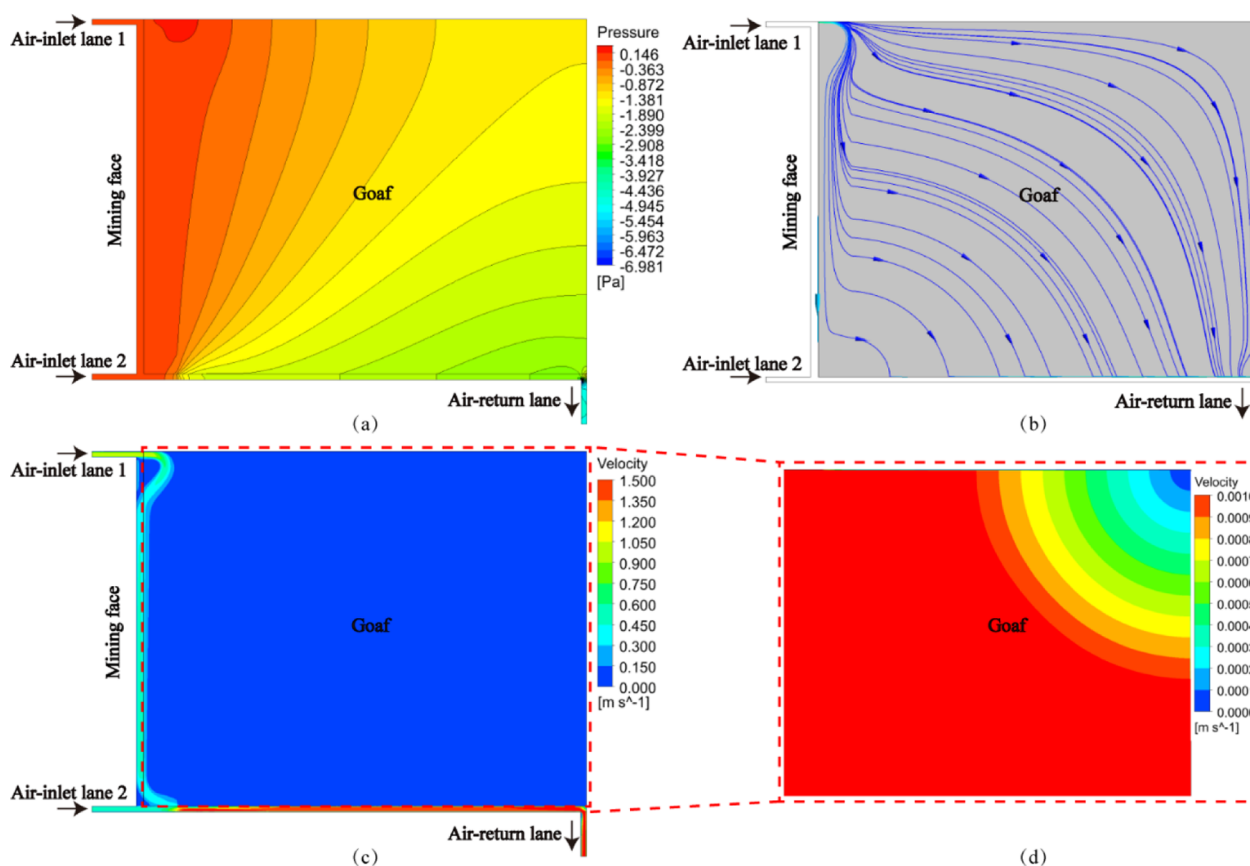

Figure 11. Roof-cutting and pressure-releasing mining mode. (a) Pressure distribution in a goaf; (b) streamline distribution in a goaf; (c) velocity distribution; and (d) velocity distribution in a goaf.

The airflow along the inclined direction of the mining face produces a small vortex area inside the goaf during the flow process. The formation of these small vortex areas is mainly attributed to the fact that after the air flows through the turn, the flow velocity is large and the turning curvature radius is small. Under the action of inertia, a vortex area is formed inside the goaf and some of the air flows into the goaf. At the end of the mining face near the air-inlet lane 2, there is also a large vortex area. This is because it is located at the intersection of two airflow currents, which easily forms a turbulent flow zone, and the air flowing through the mining face also passes through the turning point. Under the centrifugal effect, there also

appears a deceleration and pressurization zone, and then, a vortex zone appears. According to Figure 11a, the pressure gradient is the largest at the corners of the mining face, which corresponds to the maximum airflow velocity in the goaf in the velocity contour map at the corners. The airflow pressure in the air-inlet lane is the highest, whereas that at the retaining section of the air-return lane gradually decreases along the direction of the gob-side entry retention.

Figure 12a,c shows the distribution of the mining face along the section and the airflow exchange distribution in the roof-cutting and pressure-releasing mining mode, respectively. The positive value of the air volume represents the air volume from
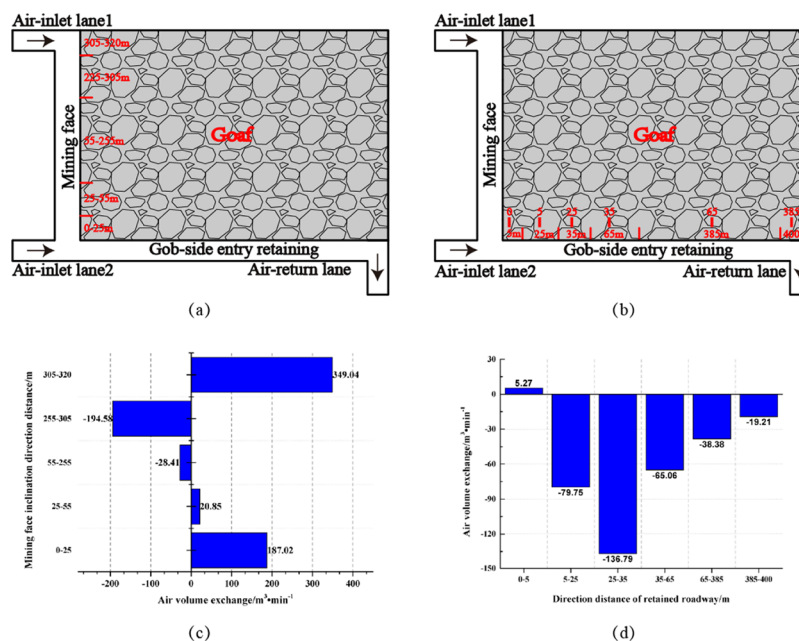
Figure 12. (a) Division of the mining face; (b) division of the gob-side entry retaining; (C) distribution map of air volume exchange along the mining face; and (d) distribution map of air volume exchange along the gob-side entry retaining.

the work face into the goaf, and the negative value of the air volume represents the air volume from the goaf back to the mining face. As shown in Figure 12c, along the inclination direction of the mining face, the sections of 0−25, 22−55, and 305−320 m are the areas where the airflow is from the mining face to the goaf. The 55−305 m section along the inclination direction of the mining face is the area where the air current escapes from the goaf to the mining face. The total airflow from the mining face into the goaf is 556.91 m³/min, accounting for 49.50% of the total air distribution. The 0−25 and 305−320 m sections are serious areas where airflow enters the goaf. The inflow air volume is 187.02 and 349.04 m³/min, respectively, accounting for 33.58 and 70.75% of the total inflow air volume. The reason for the serious air current entering the area here is also that at the entrance of the air inlet lane, the air current is injected vertically into the goaf. The total air volume escaping from the goaf along the direction of the inclination of the mining face is 222.99 m³/min. The escape air volume in the section 255−305 m is 194.58 m³/min, accounting for 87.30% of the total escape, which is the main escape area. This is due to the existence of the vortex zone, which causes the airflow from the mining face to the goaf to return to the mining face.

Figure 12b,d shows the distribution of the section distribution and the air volume exchange along the gob-side entry retaining in the goaf area. The positive value of air volume represents the air volume flowing into the goaf from the gob-side entry retention, and the negative value of the air volume represents the air volume escaping from the goaf to the gob-side entry retaining. As shown in Figure 12d, the airflow in the gob-side entry retaining section only enters the goaf from the gob-side entry retaining within the range of 0−5 m and the inflow air volume is only 5.27 m³/min. In addition, the incoming air volume is only 5.27 m³/min, all air currents in the remaining sections escape from the goaf to the gob-side entry retaining, and the total air volume of the escape is 339.19 m³/min. The escaping air volume in the 25−35 m section is 136.79 m³/min, which accounts for 40.33% of the total escaping air

volume, and is the main escape area in the gob-side entry retaining. The 65−385 m section is a stable area of airflow exchange, and the air volume escaping into the gob-side entry retaining accounts for 11.32% of the total air volume escaping.

Figure 13 shows the airflow disturbance area in the goaf under the roof-cutting and pressure-releasing mining mode,
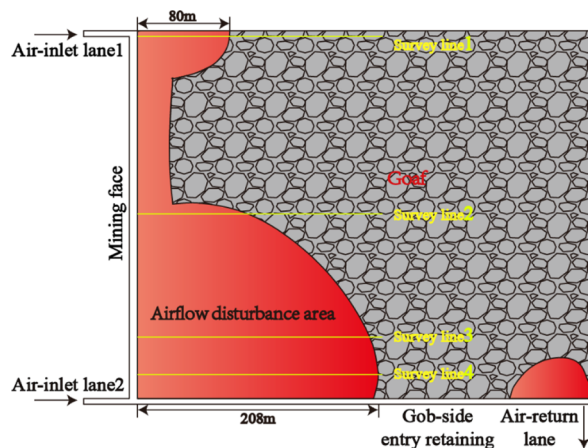

Figure 13. Airflow disturbance area in the goaf under the roof-cutting and pressure-releasing mining mode.

according to the simulation results. Here, the airflow disturbance in the goaf is approximately in the form of a "hump." The range of disturbance gradually decreases from the side of air-inlet lane 1 to the middle of the goaf, and then, the range of disturbance continues to increase from the middle to the side of air-inlet lane 2. The side airflow disturbance depth near air-inlet lane 2 reaches a maximum at a distance of 208 m, that near air-inlet lane 1 is 80 m, and the minimum disturbance depth area is located between air-inlet lane 1 and the middle of the goaf, with a distance of 30 m. The main area of airflow disturbance in the goaf under the roof-cutting and pressure-releasing mining mode ranges 0−208 m. In addition, there is a

"mountain-peak-type disturbance area in the vicinity, with a small range. It is because that this zone is located near the air return lane, where the airflow pressure inside the goaf is the lowest, and the direction of the airflow when it meets the boundary of the goaf changes. At the same time, the average air leakage at 385−400 m on gob-side entry retaining in the goaf is far greater than that at 65−385 m. Therefore, the airflow will form a turbulent area here, which will disturb the goaf. To describe the degree of airflow disturbance in the goaf, four velocity survey lines are arranged according to the disturbance pattern of the goaf, each of which is 120 m long. Survey line 1 is 3 m away from the side of air-inlet lane 1, survey line 2 is 160 m from the air-inlet lane side of the goaf center line, survey line 3 is 60 m away from the air-inlet lane 2 side, and survey line 4 is 22 m away from the air-inlet lane 2 side.

The velocity distribution data along the goaf strike are obtained by monitoring the four survey lines, intercepting the data within the range of 30−220 m, and drawing a velocity point line diagram as shown in Figure 14. Here, the inflow
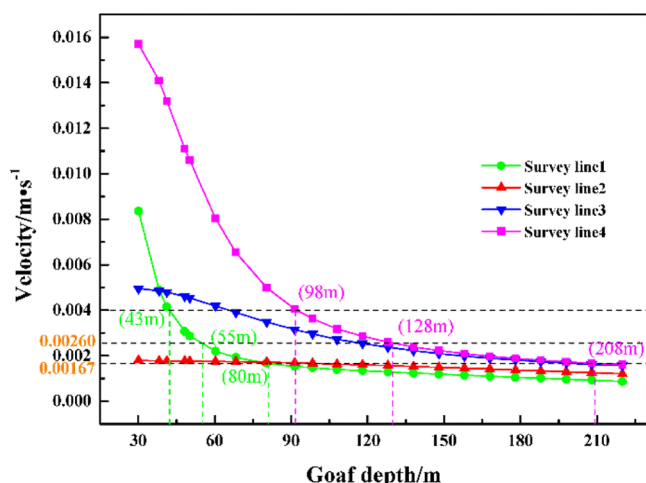

Figure 14. Velocity point line diagram along the strike of the goaf.

airflow speed gradually decreases along the goaf direction. The airflow speed is the highest in the goaf near air-inlet lane 2 and the lowest in the middle of the goaf. In addition, the airflow speed along the side near air-inlet lane 2 is always higher than that near the side of air-intake lane 1 and the middle of the goaf. Figure 15 shows a distribution diagram of the degree of airflow disturbance in the goaf. Here, under the roof-cutting and pressure-releasing mining mode, the range of the moderately disturbed area of the airflow near inlet-lane 1 in the strike direction of the goaf is 0−43 m and the area near air-inlet lane 2 ranges 0−98 m. Figure 11a shows that under the roof-cutting and pressure-releasing mining mode, owing to the change in ventilation mode, the airflow pressure near the mining face is high, especially at the corners of the mining face. Therefore, there are no overlimit disasters of gas in the mining face caused by gas escaping from the goaf. Figures 14 and 15 show that the range of the area of moderate airflow disturbance near the air-inlet lane 1 is 0−43 m and that near air-inlet lane 2 is 0−98 m. The area of severe airflow disturbance near air-inlet lane 1 ranges 43−55 m and that near air-inlet lane 2 ranges 98−128 m. The area of slight airflow disturbance on the side of air-inlet lane 1 is 55−80 m, and the area on side of the air-inlet lane 2 ranges 128−208 m. The area of undisturbed airflow is 80 m after approaching the side of the air-inlet lane 1 and 208 m after approaching the side of the air-inlet lane 2.

5. DISCUSSION

An analysis of the characteristics of the airflow movement in the goaf under the traditional longwall mining mode and the roof-cutting and pressure-releasing mining mode indicates that the two mining modes have significant differences in terms of the law of airflow movement in the goaf.

From the perspective of inflow air volume, in the traditional longwall mining mode, the total airflow from the mining face to the goaf is 133.06 m^3/min, whereas under the roof-cutting and pressure-releasing mining mode, the total airflow from the mining face and the reserved lanes into the goaf is 562.18 m^3/min. From the perspective of the number of sources of airflow entering the goaf, only one source of airflow enters the goaf under the traditional longwall mining mode, which is located in the 0−5 m section along the inclination direction of the mining face. Under the roof-cutting and pressure-releasing mining mode, there are two places, where the air mainly flows into the
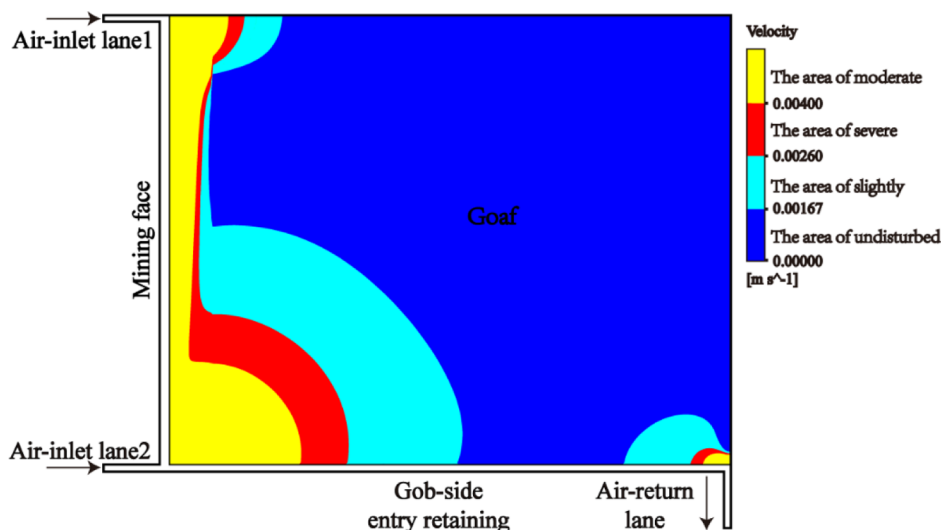

Figure 15. Distribution of the degree of airflow disturbance in the goaf under the roof-cutting and pressure-releasing mining mode.

goaf: the 305−325 m section along the inclination direction of the mining face is the main source of airflow and the 0−25 m section is the secondary source. Thus, compared with the traditional longwall mining mode, the main source of airflow in the goaf exhibits an increase in the roof-cutting and pressure-releasing mode. From the perspective of airflow escape area, the main airflow escape area under the traditional longwall mining mode is the 15−45 m section along the inclination direction of the mining face and the 45−315 m section is the stable airflow escape area. However, there are two main airflow current escape areas and two stable airflow current escape areas under the roof-cutting and pressure-releasing mining modes. The 255−305 m section of the goaf along the inclination direction of the mining face and the 25−35 m section along the direction of the side of the gob-side entry retaining are the main airflow escape areas. The 55−255 m section along the inclination direction of the mining face and the 65−385 m section on the side of the gob-side entry retaining are the stable airflow escape areas. These two areas have a wide range but a small escape air volume. From the perspective of airflow disturbance depth in the goaf, the airflow disturbance depth in the goaf is 106 m in the traditional longwall mining mode and 208 m in the roof-cutting and pressure-releasing mining mode. In addition, the airflow disturbance pattern in the goaf changes from "η" type to "hump" type. From the perspective of the degree of airflow disturbance, the width of the traditional longwall mining mode in the area of severe airflow disturbance is 24 m and that of the roof-cutting and pressure-releasing mining mode is 30 m, which is not significantly different. In the traditional longwall mining mode, the area of moderate airflow disturbance is 66 m and that of the roof-cutting and pressure-releasing mining mode is 98 m. Although the difference between the two is 32 m, the main disaster factor in this area is gas over-run. In the traditional longwall mining mode, gas accumulates in the upper corner of the mining face. In contrast, in the roof-cutting and pressure-releasing mining mode, the change in the ventilation system addresses the problem of gas over-run in the upper corner, which is safer by comparison. In addition, the width of the area slightly disturbed by the airflow is 19 m in the traditional longwall mining mode and 80 m in the roof-cutting and pressure-releasing mining mode. Thus, the roof-cutting and pressure-releasing mining mode is safer in the area of moderate airflow disturbance, which is not much different from the traditional longwall mining mode, and is larger in the area of slight airflow disturbance.

The hanging airflow tent is a simple and effective method to prevent airflow generated from the mining face from entering the goaf. Under the roof-cutting and pressure-releasing mining mode, the air tents are suspended in the 0−25 and 305−325 m sections of the main airflow in the mining face direction, which can effectively prevent the airflow generated from the mining face from entering the goaf. The necessary and sufficient condition for airflow exchange in the goaf is the existence of a channel, and there is a pressure difference between the two ends of the channel. Whether the airflow is into or out of the goaf, the final airflow enters the reserved lane from the goaf through the interface between the reserved lane and goaf. Under the effect of the pressure difference between the reserved lane and gob area, the gas in the gob area gushes into the reserved roadway through the cracks in the wall of the reserved roadway. To further reduce the risk of ignition of the remaining coal in the goaf, it is necessary to spray grouting on the roadway section of the goaf to reduce the airflow exchange between the goaf and the mining face.

6. CONCLUSIONS

This study analyzes the differences in mining technology and the roof-caving characteristics between the traditional longwall mining mode and roof-cutting and pressure-releasing mining mode. Based on the 1201 mining face of the Halagou Coal Mine, the airflow characteristics of the goaf under these two mining modes are studied by numerical simulations and on-site measurements. The main results were obtained as follows.

The characteristics of airflow exchange in a goaf are different between the roof-cutting and pressure-releasing mining mode and the traditional longwall mining mode. Under the traditional longwall mining mode, the air leakage distribution shows a shape of a "⊃" in the goaf. There are two main airflow exchange areas in the goaf. Along the inclination direction of the mining face, the airflow exchange areas are located in the 0−5 and 15−45 m sections, respectively. The airflow exchange is 133.06 m^3/min between the mining face and goaf. Under the roof-cutting and pressure-releasing mining mode, the air leakage distribution has a shape of a "1/4 arc" in the goaf. There are six main exchange areas for the airflow in the goaf. Along the inclination direction of the mining face, the exchange areas are located in the 0−25, 255−305, and 305−320 m sections, respectively. Along the strike direction of the goaf, the exchange areas are located in the 5−25, 25−35, and 35−65 m sections, respectively. The airflow exchange capacity is 556.91 m^3/min between the mining face and goaf.

The distributions of airflow disturbance area in a goaf are different between the roof-cutting and pressure-releasing mining mode and the traditional longwall mining mode. Under the traditional longwall mining mode, the airflow disturbance area appears in the shape of a "η" in a goaf. The depth of the airflow disturbance area is 106 m. The slight, moderate, and severe airflow disturbance area is 19, 66, and 24 m, respectively. Under the roof-cutting and pressure-releasing mining mode, the airflow disturbance area shows the shape of a "hump". The airflow disturbance area in the goaf is 208 m. The slight, moderate, and severe airflow disturbance area is 80, 98, and 30 m, respectively.

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Notes

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