

Article

Study on the Concentration Distribution of Gas in the Heading Face and Optimization of Duct Arrangement

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Abstract

Coal mine gas is one of the primary hazards encountered in mining operations. The continuous emission of gas in the heading face during tunneling poses potential dangers, with a significant likelihood and magnitude of gas-related accidents. Tunnel ventilation not only dilutes the concentration of pollutants but also ensures underground air quality, safeguarding the physical and mental health of workers. Therefore, underground tunnel ventilation is particularly crucial. Analyzing the airflow field in single-heading tunnels and optimizing ventilation layout are of paramount practical significance for ensuring mining safety. Initially, based on engineering realities, on-site experimental measurements were conducted in the simulated area of the single-heading tunnel. The essential parameters for ventilation simulation were obtained, and a numerical three-dimensional model of the ventilation in the single-heading tunnel was established using Fluent software. Subsequently, through numerical simulations, the airflow field and gas concentration distribution patterns in the single-heading tunnel were obtained. It was verified that the tunnel airflow field exhibits distinct layering and uneven distribution. Gas concentration on the return air side is higher than that on the intake air side, with elevated gas concentrations in the upper corner and the lower right corner on the return air side. Further, four main factors influencing gas concentration were identified: duct diameter, duct exit velocity, distance from the duct exit to the heading face, and the suspension position of the duct. Finally, an orthogonal design approach was employed, and numerical simulations were conducted to study the sensitivity of these factors to gas concentration. The optimal ventilation layout was determined and validated: a duct diameter of 0.7 m, an airspeed of 13 m/s (without considering a fixed air volume), a distance of 7 m from the duct exit to the heading face, and the duct suspended in the lower part of the tunnel. The stabilized gas concentration under these conditions was determined to be 0.1378%.



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Keywords: gas distribution; heading face; numerical simulation; flow distribution; orthogonal test

1. Introduction

Coal resources remain an essential foundation for the development of human society. In China, coal is expected to maintain its dominant position in the energy structure for an extended period [1–4]. During the underground mining process, the release of hazardous gases with explosive potential often accompanies the extraction of coal [5]. The safety of

underground coal mining is significantly constrained by the presence of methane gas [2]. Methane, as an inherent byproduct of underground coal extraction, can lead to major natural disasters if its concentration exceeds safety limits [6,7]. Methane-related accidents are among the most serious hazards in Chinese coal mines [8]. As shown in Figure 1, according to incomplete statistics, China has experienced 346 methane accidents since 2009, resulting in 2714 fatalities [9,10]. In the process of mining operations, the heading face of a single-heading tunnel is one of the most important workplaces underground and is also a major source of hazardous substances. From a production safety perspective, it is imperative to remove methane from the single-heading tunnel through a ventilation system [11,12]. Press-in ventilation is an effective, simple, and economical method to prevent the accumulation of methane and the risk of explosions, making it the most widely used ventilation method [13]. Currently, with the increase in coal mining depth and mechanization levels, methane concentrations have significantly risen, and the corresponding ventilation arrangements are challenging to optimize for the best results [14,15]. Therefore, studying the airflow patterns and methane distribution in the single-heading tunnel and optimizing the placement of ventilation ducts are of paramount importance for achieving safe and environmentally friendly coal mining production underground.

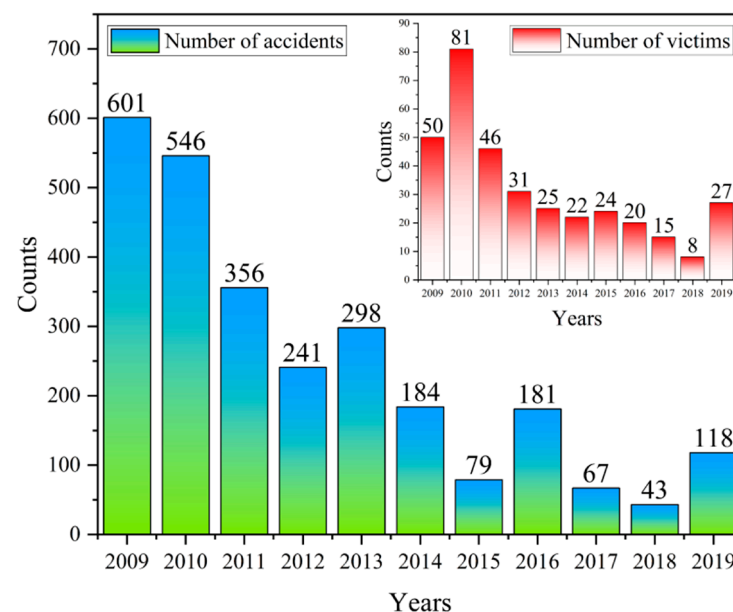


Figure 1. Gas accidents and casualty statistics in China (2009–2019).

Scholars worldwide have conducted extensive research on the airflow patterns and methane concentration distribution in underground coal mines and gas-containing underground projects. Computer numerical simulation has found widespread application in this field, including computational fluid dynamics (CFD) techniques [16–21]. Parra and Toraño et al. conducted numerical simulations of airflow under various ventilation schemes and verified the applicability of the CFD model simulation [12,22]. Hargreaves and Lowndes used a CFD model and full-scale experiments to investigate airflow in galleries during continuous mining processes [23]. Fang et al. discovered that installing exhaust outlets near the working face effectively dilutes harmful gases [24]. Magesh et al. conducted numerical simulations treating airflow and coal dust in the fully mechanized mining face separately as continuous and discrete phases, respectively, providing a comparative analysis of different simulation methods for coal dust distribution patterns [25]. Lu et al. utilized CFD methods to numerically study methane and dust concentrations in continuous mining faces, finding that the presence of continuous miners leads to increased

methane and dust concentrations [26]. Wang et al. established a mathematical model to determine the methane emission rates at various locations in fully mechanized mining faces. They conducted numerical simulations for six typical working conditions, obtaining the dispersion patterns of methane in fully mechanized mining faces and identifying the main influencing parameters [27,28]. Tutak and Brodny numerically simulated the diffusion of return air corner gas in fully mechanized mining faces and the impact of auxiliary ventilation on the distribution pattern of gas. Additionally, they conducted a detailed analysis of airflow and gas trajectories, confirming the superiority of auxiliary ventilation equipment [29]. Ren et al. dynamically studied the airflow and coal dust at the intersection of the fully mechanized coal mining face and the intake airway, proposing an optimized arrangement of the intake airway and the entrance curtain based on numerical simulation results [30]. Cai et al. numerically simulated the impact of airflow on dust diffusion in fully mechanized mining faces, studying dust diffusion characteristics under different air volumes and ultimately determining dust concentrations under different air volumes [31]. Zhou et al. used CFD simulation to study the temperature and airflow velocity distribution in different types of inclined urban tunnels, providing reference information for ventilation system management and air quality improvement [32]. Li et al. employed a combined approach of theoretical calculations and numerical simulation to summarize the impact of airflow channel width on airflow characteristics [33,34]. They observed that air closer to the heat-absorbing wall has a higher velocity, noting a critical channel width. When the channel width exceeds this critical width, airflow direction and velocity become unstable, leading to possible backflow.

In summary, numerous scholars have conducted extensive research and achieved certain results. Previous studies have provided a comprehensive understanding of gas flow fields and distribution patterns in the heading face. However, there is limited research on the distribution patterns of gas concentration and the optimization of fan placement in the heading face. Therefore, based on the actual heading face of a coal mine, this study draws upon engineering practice and utilizes methods such as on-site experiments, fluid numerical simulations, and theoretical analysis. It aims to simulate the ventilation flow field in the heading face and optimize fan placement. This research provides a basis for the arrangement of fans in the heading face and the control of gas concentrations. It aims to achieve the most effective fan arrangement in the heading face of a coal mine, facilitating the efficient removal of gas, improving ventilation efficiency, reducing accident rates, and providing significant practical value for ensuring the safety of mining production.

2. On-Site Monitoring of Wind Speed and Gas in the Heading Face

2.1. The Project Overviews

The Central Bridge Coal Mine is located northwest of the urban area of Yongchuan District, with an orientation of approximately 327°. It is situated about 13 km in a straight-line distance from the urban area of Yongchuan District, falling under the jurisdiction of Shuangshi Town, Yongchuan District. The mine extends south to the Xiehe Coal Mine in Yongchuan City, north to the Yonghe Wellfield in Yongchuan City, and west to Changhe Coal and Electricity Company. The asphalt road from the mine travels south for 7.5 km, connecting to Taiping and Lao Chengyu roads, and then continues for another 7.5 km along Chengyu Road to the Shuangshi Bridge railway station of the Chengdu–Chongqing Railway. It is 22 km from the junction of Yongchuan City and the Chengdu–Chongqing Expressway, making it easily accessible, as illustrated in Figure 2a, which depicts its transportation location.

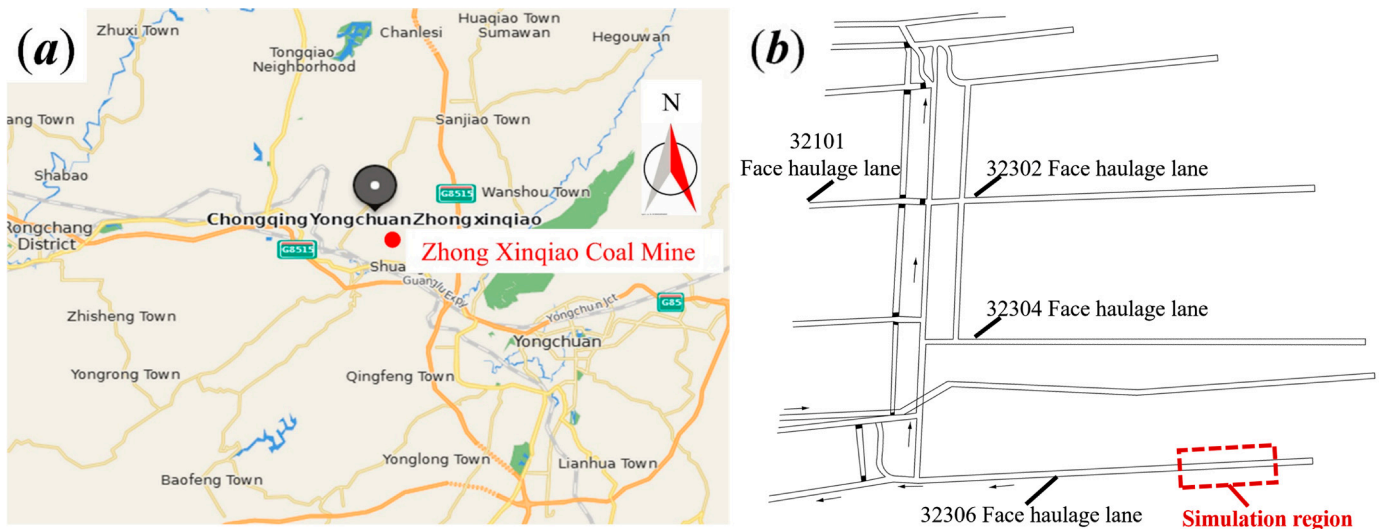


Figure 2. Transportation location and the layout plan of the 300 m horizontal roadway at the Central Bridge Coal Mine. (a) The geographical location of the central bridge coal mine; (b) The schematic diagram of the simulation region of the 32306 Face haulage lane.

The transport roadway of the 32306 working face in the on-site monitoring area is located in the fifth stratigraphic layer of the Triassic Xujiahe Formation, arranged along the direction of the K2 coal seam. The 32306 transport roadway is situated to the south of the northern part of the -300 m outer coal group in the Second Mining Area, with the transport roadway of the 32304 working face above it. To the south is the return air uphill to the north boundary of the northern wing of the -300 m level, and to the north is the yard of the Second Mining Area. The lower part has not been mined. The layout plan of this working face and the nearby horizontal roadways is illustrated in Figure 2b.

2.2. Site Testing and Data Analysis

A schematic diagram of single-head roadway ventilation under forced ventilation is presented in Figure 3a. The layout of wind speed measuring point 1 is shown in Figure 3b, and gas concentration measuring points 2, 3, and 4 are arranged as displayed in Figure 3c. Their vertical distances from the roadway floor are 1.6 m, 0.3 m, and 1.8 m, respectively. Sections at positions 2 m, 7 m, 17 m, 22 m, 27 m, 32 m, 37 m, 42 m, 47 m, and 57 m from the face were selected as the measurement sections. The DFA-3 low-speed anemometer and CJG10 optical methane detector were used to measure the airspeed and gas concentration of the heading face in the advancing working face. Measurements were repeated three times at each point in each section, and the average values were taken to draw the curves of airspeed and gas concentration, as shown in Figure 4.

According to the wind speed variation curve, under the actual ventilation arrangement, the wind speed at the working face heading is lower than that at a position about 2 m away from the working face. Due to the jet diffusion and suction effect, there is a vortex zone around 2–7 m away from the working face, where the wind speed decreases to a minimum. Beyond 7 m from the working face, the wind speed gradually increases and eventually stabilizes. According to the gas concentration variation curve, it can be observed that the gas concentration is minimal near the working face and gradually increases as the distance becomes greater, reaching a certain value and then remaining stable.

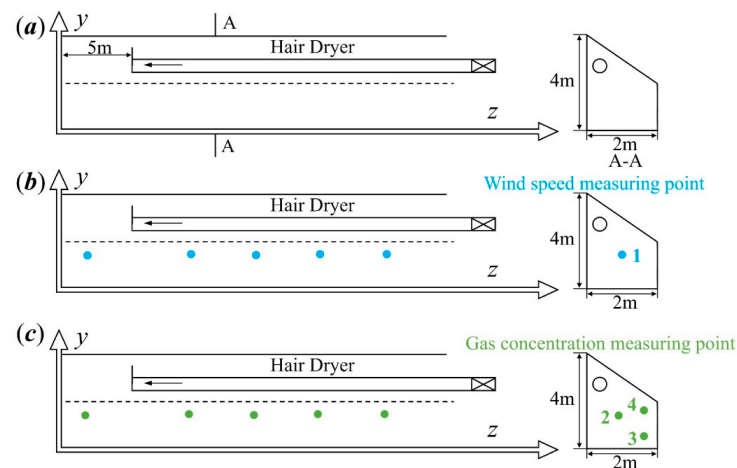


Figure 3. (a) Press-in ventilation schematic, (b) wind speed measurement point layout, and (c) concentration measurement point layout.

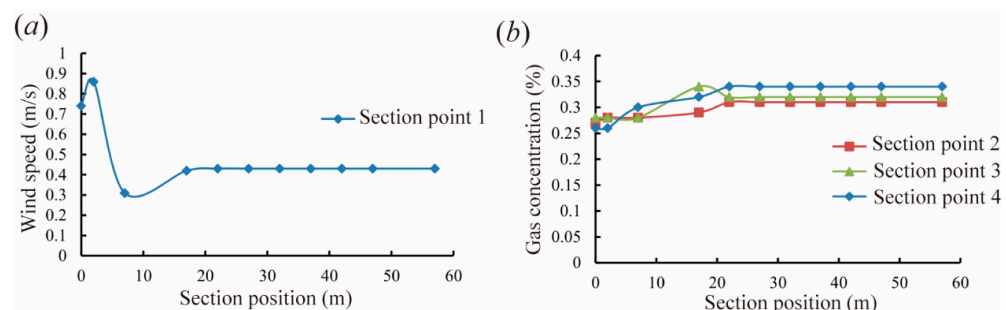


Figure 4. Variations in wind speed and gas concentration at different positions along different sections. (a) The wind speed change of the section point 1; (b) The gas concentration change of the section point 2, 3, 4.

3. Numerical Simulation Study of Ventilation and Gas Distribution in Single-Head Entry Roadways

3.1. Mathematical Model

Before selecting the control equations, it is necessary to determine the flow regime of the fluid. The fluid in the study area is characterized by the flow of gas, and the flow regime is determined based on the Reynolds number of a non-circular cross-sectional shaft:

$$Re = 4 \frac{uS}{vU} \quad (1)$$

where u represents the average fluid velocity, S is the cross-sectional area of the roadway, v is the dynamic viscosity coefficient of the fluid, and U is the perimeter of the roadway. With a cross-sectional area of 9 m^2 , a roadway perimeter of 12.6 m , and a fluid dynamic viscosity coefficient of $1.8 \times 10^{-5} \text{ m}^2/\text{s}$, and considering the minimum measured airflow in the roadway as 0.23 m/s (as determined in the previous chapter), the Reynolds number Re is approximately 36,508. This value is significantly greater than the critical value of 8000, indicating that the airflow in the studied roadway is in a turbulent state.

After determining the fluid flow state, certain simplifications and settings need to be made for on-site conditions and numerical simulation based on engineering reality.

- (1) The airflow in the heading roadway is treated as incompressible viscous flow.
 - (2) Airflow is considered to be stable turbulence, meeting the Boussinesq assumption.
- The governing equations can be based on the Reynolds equation (turbulent flow),

and a turbulence model using the turbulent kinetic energy (k) and dissipation rate (ϵ) equations is adopted.

- (3) The assumption is made that the temperature within the heading roadway airflow is constant, there is no heat source, and thermal radiation from surrounding rocks is neglected. The wall of the heading roadway is simplified as a planar boundary with roughness. The influence of personnel walking and roadway equipment on the airflow is not considered.
- (4) There are no other pollution sources in the roadway, and gas uniformly emanates from the heading face. Gas emanation from other locations is not considered.

3.1.1. The Continuous Equation

The continuous equation, also known as the law of mass conservation, can be expressed as the increase (or decrease) in mass of a fluid element per unit time being equal to the net mass added (or subtracted) during the same time period through exchange with the surroundings. The continuous equation can be mathematically represented as follows [8]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \quad (2)$$

where ρ represents the fluid density, and u , v , w are the respective x , y , z components of the flow velocity, while t represents time.

3.1.2. The Momentum Equation

The conservation of momentum equation, also known as the N-S equation, expresses that the change in momentum of a fluid element during its motion is equal to the total force acting on it from the surroundings per unit time. This law, inherently following Newton's second law, leads to the derivation of momentum conservation equations in the three directions of a coordinate system [15,35]:

$$\frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = \mu_{eff} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) - \frac{\partial p}{\partial x} = 0 \quad (3)$$

$$\frac{\partial(\rho vu)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = \mu_{eff} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) - \frac{\partial p}{\partial y} = 0 \quad (4)$$

$$\frac{\partial(\rho wu)}{\partial x} + \frac{\partial(\rho wv)}{\partial y} + \frac{\partial(\rho ww)}{\partial z} = \mu_{eff} \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) - \frac{\partial p}{\partial z} = 0 \quad (5)$$

where p is the pressure of the fluid, and μ_{eff} is the effective dynamic viscosity of the fluid.

3.1.3. Turbulence Model

The standard k - ϵ model is based on the k equation model, introducing an additional equation for the turbulent dissipation rate ϵ . This k - ϵ model is currently the most widely used turbulence model in software simulation processes, and its expression is as follows [36,37]:

$$\frac{\partial(\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k - \rho \epsilon \quad (6)$$

$$\frac{\partial(\rho u_i \epsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} \right] + c_{1\epsilon} \frac{\epsilon}{k} G_k - c_{2\epsilon} \rho \frac{\epsilon^2}{k} \quad (7)$$

with

$$G_k = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad (8)$$

where G_k represents the generation term of turbulent kinetic energy k caused by the mean velocity gradient, $c_{1\varepsilon}$ and $c_{2\varepsilon}$ are empirical constants, and σ_k and σ_ε are the Prandtl numbers corresponding to turbulent kinetic energy k and turbulent dissipation rate ε , respectively. According to recommended values and experimental verification by Launder et al., the constants are $c_{1\varepsilon} = 1.44$, $c_{2\varepsilon} = 1.92$, $\sigma_k = 1.0$, and $\sigma_\varepsilon = 1.3$.

3.1.4. Mass Conservation Equation for Components

In a specific fluid system, there may be changes in fluid composition or variations in multiple chemical components, but any component must adhere to the mass conservation equation for components [14,38]. Therefore, for similar fluid systems, the law of mass conservation of components can be summarized as follows: within a unit of time, the change in a certain component within the system will be manifested in another form. If there are chemical reactions between components, the change in mass of component s is then represented by diffusion flux and the mass resulting from the reaction. The mass conservation equation for component s is expressed as follows:

$$\frac{\partial(\rho c_s)}{\partial t} + \text{div}(\rho \vec{v} c_s) = \text{div}(D_s \text{grad}(\rho c_s)) + S_s \quad (9)$$

where c_s and ρc_s represent the volume concentration and mass concentration of component s , respectively. D_s is the diffusion coefficient of the component, and S_s is the mass generated by chemical reactions within the system per unit time, which is the production rate. Because $\sum S_s = 0$, expressing the mass control equation for each component, combining these component control equations results in the continuity equation.

3.2. Numerical Model Construction

3.2.1. Geometric Model

This study focuses on the excavation face of the 32306 haulage roadway in the mine as the research object. The excavation face adopts a press-in local method, and the roadway section is wedge-shaped, referred to as a wedge roadway. The single-head excavation roadway's ventilation duct is installed on the left side (inflow side) of the roadway, in the upper part of the wall, at a distance of 3 m from the ground. The ventilation duct has a diameter of 0.6 m. The height of the roadway side on the inflow side is 4 m, and that on the outflow side is 2 m. The roadway width is 3 m, and the ventilation duct's outlet is 5 m away from the sealing section of the working face. The outlet velocity of the ventilation duct is 11.8 m/s, and the net cross-sectional area of the roadway is 9 m². Considering the actual conditions of the working face, the mechanical equipment in the three-dimensional single-head excavation roadway is simplified to a certain extent. This article uses the pre-processing software Gambit 2.2.30 to establish a three-dimensional geometric model. The excavation direction is considered the negative direction of the Z-axis, and the roadway's cross-section is in the XY plane. The schematic diagram of the geometric model is shown in Figure 5, and the mesh division is shown in Figure 6.

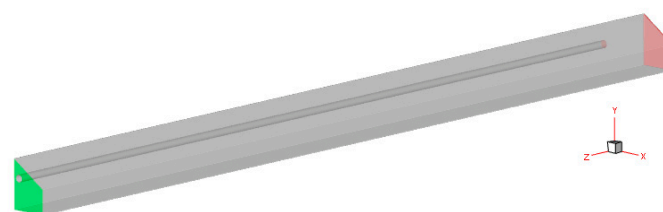


Figure 5. Three-dimensional geometric model of the single-head entry.

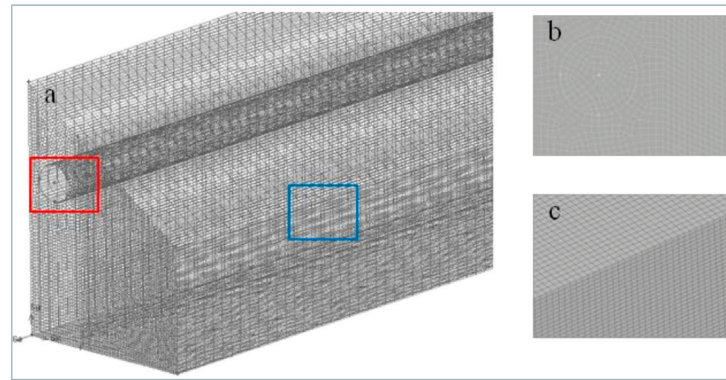


Figure 6. Structured and unstructured mesh division of the single-head entry roadway. (a) Mesh division of the whole model; (b) Mesh division of air duct; (c) Mesh division of wall.

3.2.2. Parameter Settings

When simulating with FLUENT 6.3.26, the focus is on studying the patterns after fluid stability is achieved, in order to subsequently investigate the importance of influencing factors. The chosen solver, operating environment, and relevant parameters for the computational model and materials are outlined in Table 1.

Table 1. Settings of FLUENT simulation parameters.

Parameter Names	Parameter Values
Solver	Pressure-based solver
Spatial discretization	Three-dimensional (3D)
Speed formula	Absolute
Pressure	Standard atmospheric pressure
Acceleration due to gravity	−9.8 (z-direction)
Energy	Energy equation
Turbulence model	k - ϵ model
Species model	Species transport model
Radiation model	Off
Discrete phase model	Off
Material	Methane-air
Velocity–pressure coupling method	SIMPLE
Under-relaxation factor	Default
Discretization scheme	First order upwind

Based on the geometric model and known parameters, the basic boundary conditions for the heading tunneling face model are set as follows: (1) gas source term: the first two layers of grids (0.1 m) at the heading are set as the gas source term; (2) wall boundary conditions: the tunnel walls are treated as non-slip solid walls; (3) outlet boundary conditions: the cross-section of the tunnel 100 m away from the face is set as the outflow boundary condition, ensuring that it is outside the stable range of the flow field; (4) inlet boundary conditions: the small circular face of the vent outlet is set as the velocity inlet, and the specified velocity is set as the average velocity of the vent outlet, with the direction perpendicular to the boundary face of the vent outlet.

3.3. Analysis of Numerical Simulation Results

We conducted numerical simulations of the three-dimensional airflow in the tunnel face using FLUENT 6.3 software. The analysis focused on the distribution patterns of the airflow and methane concentration. The obtained results were compared and analyzed in conjunction with experimental data measured in the tunnel.

3.3.1. Analysis of the Airflow Field in the Single-Heading Tunnel

Figure 7 represents a three-dimensional streamline diagram of the tunnel airflow. The three-dimensional streamline visualization clearly shows the flow trajectory of the tunnel airflow. The airflow turns around at the heading of the working face, forming a backflow, and significant vortices are formed near the heading.

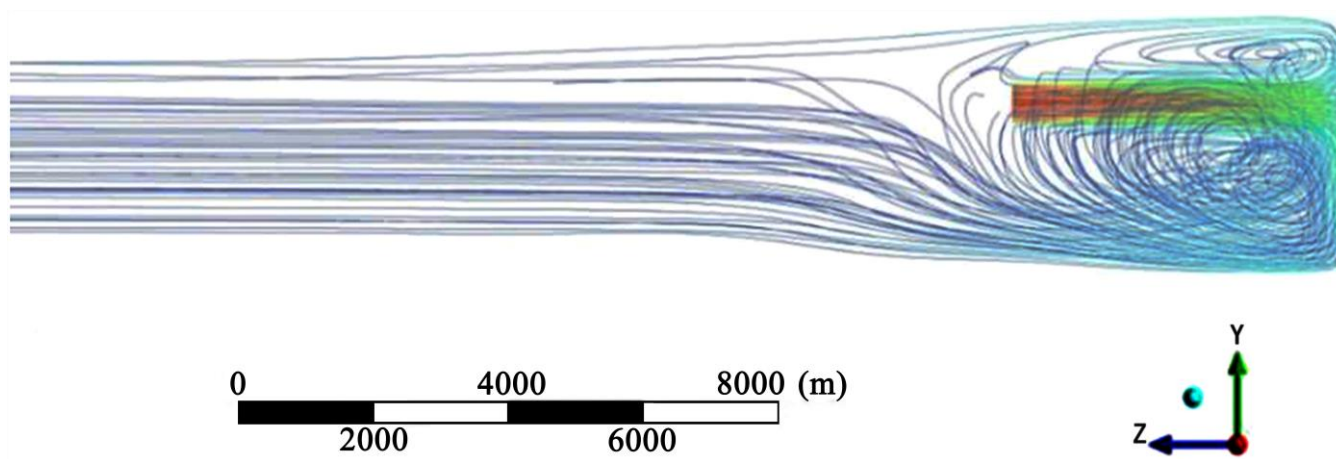


Figure 7. Three-dimensional flow diagram.

From Figure 8, it can be generally observed that the wind speed of the airflow in the lateral and longitudinal directions of the tunnel tends to stabilize after a distance of a few meters from the heading. There are still small differences in velocity on the XY plane, forming a noticeable diversion phenomenon.

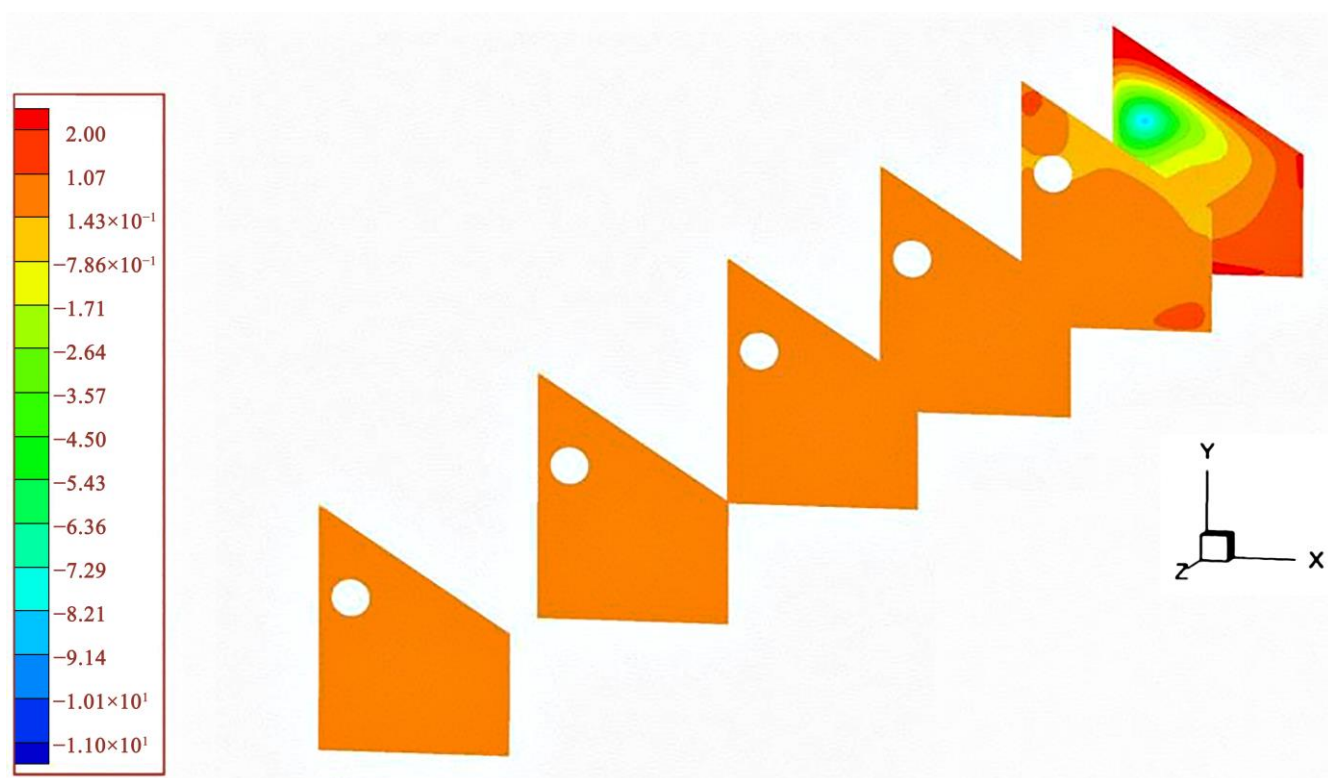


Figure 8. Velocity distribution on the XY plane.

3.3.2. Analysis of Gas Concentration Distribution in the Single-Heading Tunnel

Through post-processing software, the gas concentration in this single-heading tunnel is analyzed. Below, the distribution pattern of gas concentration is illustrated by cloud maps of different views of the tunnel and concentration curve graphs at different locations.

Figure 9 illustrates the methane concentration contour plots on the XY plane at distances of 0 m, 5 m, 10 m, 15 m, 20 m, 25 m, and 30 m from the working face heading. From the contour plots, it can be observed that the methane concentration is lowest near the working face heading, close to the jet end of the airflow, and the concentration on the intake side is lower than that on the return side. Additionally, the contour plots indicate relatively higher methane concentrations in the lower part of the return side. However, as the distance from the working face heading increases, the methane concentration stabilizes overall. Therefore, there is a need to enhance the monitoring of methane concentrations in the lower part of the return side.

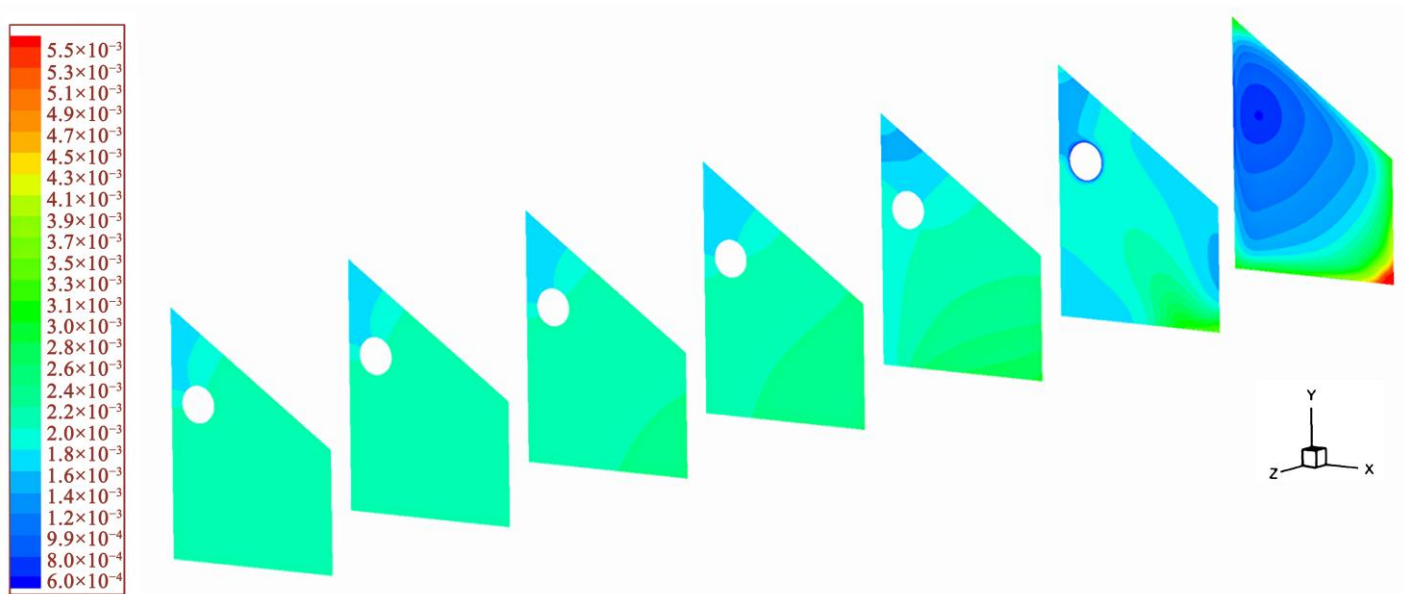


Figure 9. Gas concentration cloud on the XY plane.

3.4. Model Validation

In order to further validate the reliability of the software-simulated data, it is necessary to compare the simulated data with the on-site measured data. The on-site measurement data and the software-calculated values are plotted as a comparative curve, as shown in Figure 10.

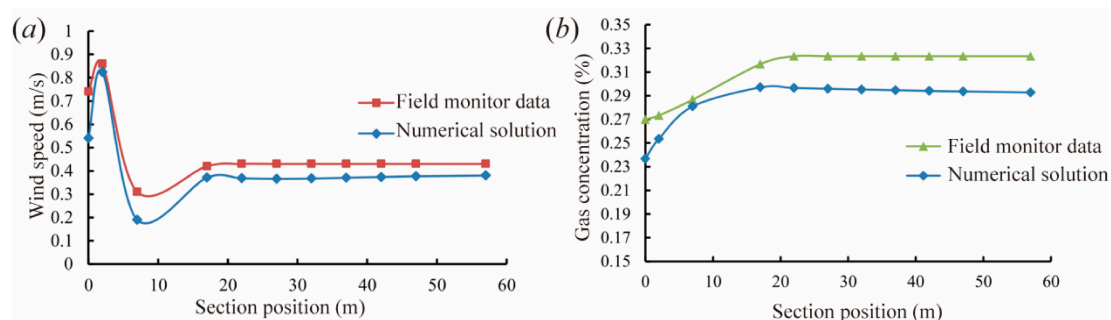


Figure 10. (a) Comparison of measured wind speed along the centerline of the tunnel with simulated wind speed, and (b) comparison of measured gas concentration on the return air side of the tunnel with simulated concentration.

According to Figure 10, it can be observed that the error between the on-site measured data of the advancing working face and the numerically simulated data is generally well controlled within an acceptable range (the average absolute errors for wind speed and gas concentration are 0.67 m/s and 0.9%, respectively). This indicates a good correlation between the on-site measured data and the numerically simulated data. The larger errors observed at some measurement points can be attributed to several factors, including the working conditions at the on-site measurement locations, errors in measurement instruments and their accuracy, simplifications in the software model, and the settings of the simulation boundary conditions. In general, however, the numerical simulation results exhibit good agreement with the on-site measured data. This further suggests that the mathematical model and numerical methods chosen in this study are appropriate. Moreover, the numerical simulation results provide a detailed description of the airflow field variations in the pressure-type local ventilation single-heading tunnel.

4. Analysis of Factors Influencing Gas Concentration in the Single-Heading Tunnels and Arrangement of Ventilation Ducts

Based on the current research results, it is known that there are many factors influencing the variation of gas concentration in the single-heading tunnel. These factors include the ventilation method of the single-heading tunnel, the gas outburst from the tunnel walls, the size of the tunnel cross-sectional area, tunnel temperature, the air supply of the ventilation fans, and the diameter and position of the air duct. In reality, for a specific advancing gas tunnel, the ventilation method is fixed under certain conditions, and the tunnel's cross-sectional area, tunnel temperature, and wall roughness are objectively fixed. Therefore, this paper, based on actual engineering coal mine tunnels and employing the pressure-type ventilation method, studies the influence of the air duct diameter, the distance from the air duct outlet to the heading of the working face, the suspension position of the air duct, and the air velocity at the air duct outlet on the gas concentration in the tunnel.

4.1. Orthogonal Experimental Analysis

4.1.1. Orthogonal Experimental Design

The orthogonal experimental method is a specialized experimental approach designed for the arrangement and analysis of experiments involving multiple factors, especially three or more factors. This method includes experimental indicators, factors, and levels. The stabilized gas concentration value is chosen as the experimental indicator. The controllable influencing factors, considered as experimental factors, are the distance from the air duct outlet to the working face (L), the suspension position of the air duct (H), the diameter of the air duct (D), and the outlet velocity of the air duct (V). The experimental levels are set based on field experience and relevant literature research, with L (8 m, 7 m, 6 m, 5 m), H (3 m, 2 m, 1.5 m, and 2.5 m on the side), D (0.7 m, 0.6 m, 0.5 m, 0.4 m), and V (13 m/s, 11.5 m/s, 10 m/s, 8.5 m/s).

The selected four factors are used as analysis factors in the orthogonal experimental design, and the stabilized gas concentration is taken as the target dependent variable to characterize the ventilation effect. The levels chosen for each factor in this experiment are shown in Table 2, and the orthogonal experimental design is presented in Table 3.

Table 2. Factor levels for the ventilation experiment.

Level	A L/m	B H/m	C D/m	D $V/m/s$
1	8	Upper	0.7	13
2	7	Middle	0.6	11.5

Table 2. *Cont.*

Level	A L/m	B H/m	C D/m	D V/m/s
3	6	Lower	0.5	10
4	5	Side	0.4	8.5

Table 3. Orthogonal design table.

Experimental Number	Factor			
	L/m	H/m	D/m	V/m/s
1	A1	B1	C1	D1
2	A1	B2	C2	D2
3	A1	B3	C3	D3
4	A1	B4	C4	D4
5	A2	B1	C2	D3
6	A2	B2	C1	D4
7	A2	B3	C4	D1
8	A2	B4	C3	D2
9	A3	B1	C3	D4
10	A3	B2	C4	D3
11	A3	B3	C1	D2
12	A3	B4	C2	D1
13	A4	B1	C4	D2
14	A4	B2	C3	D1
15	A4	B3	C2	D4
16	A4	B4	C1	D3

4.1.2. Orthogonal Experimental Results

According to the orthogonal experimental design table in the previous section and the relevant parameter settings in Section 3, the simulation experiments were conducted for the 16 experimental groups as specified. The simulation results are as follows:

(1) Experiments 1 to 4

For experiments 1 to 4, the values for L are all 8 m, the H positions are respectively upper, middle, lower, and side, the D values are 0.7, 0.6, 0.5, and 0.4, and the V values are 13, 11.5, 10, and 8.5. The gas concentration cloud maps at the heading of the working face and the concentration and wind speed variation curves along the tunnel under stable tunnel airflow conditions are shown in Figures 11 and 12.

The four cloud maps labeled as (a), (b), (c), and (d) in Figure 11 represent the gas concentration distribution at the working face for the simulated results of experiments 1 to 4. According to Figure 11, it can be observed that there is a noticeable stratification of gas concentration near the heading of the tunnel, consistent with the concentration analysis in Section 3. The closer to the air outlet, the smaller the gas concentration in the vicinity. Gas concentration is slightly higher at various corners of the tunnel cross-section, indicating that gas tends to accumulate in the corners of the tunnel. Due to different positions of the ventilation duct, the accumulation of gas concentration in the tunnel cross-section varies, with the gas concentration primarily distributed on the side away from the ventilation duct.

Combined with Figure 12, it is evident that gas concentration and wind speed undergo certain changes near the working face, with significant variations in wind speed. Gas concentration and wind speed exhibit a negative correlation, where higher gas concentration corresponds to lower wind speed, and both values tend to stabilize. The stable values of gas concentration for experiments 1 to 4 are 0.1385, 0.2125, 0.3515, and 0.6464, while the stable values of wind speed are 0.5617, 0.3587, 0.2125, and 0.1428, respectively.

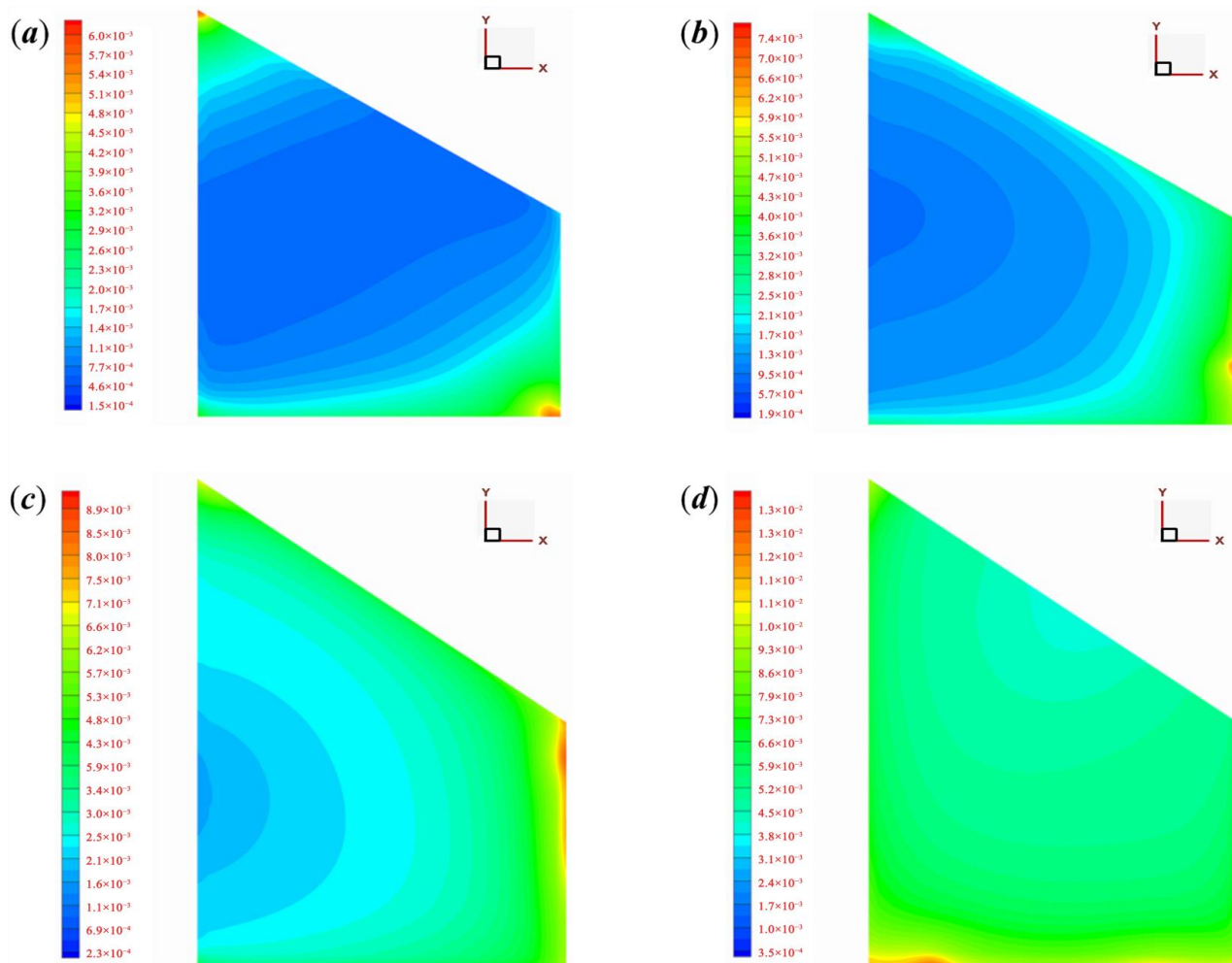


Figure 11. Gas concentration cloud of the roadway face for experiments 1–4. (a) experiments 1; (b) experiments 2; (c) experiments 3; (d) experiments 4.

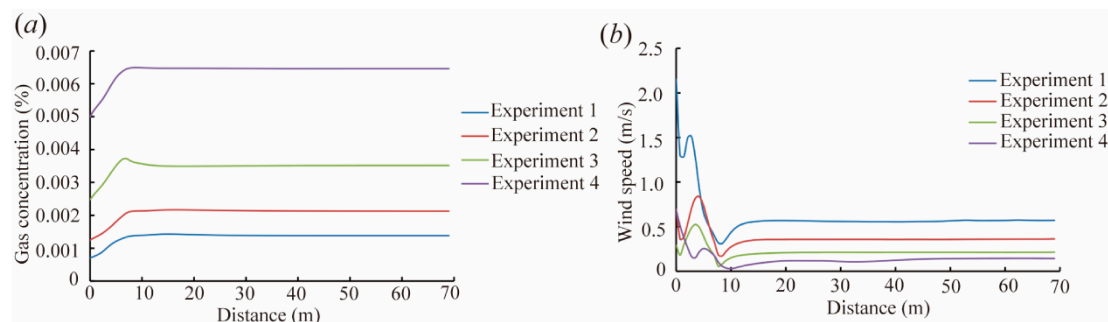


Figure 12. (a) Gas concentration variation curves along the tunnel for experiments 1–4; (b) Wind speed variation curves along the tunnel for experiments 1–4.

(2) Experiments 5 to 8

For experiments 5 to 8, the values for L are all 7 m, the H positions are respectively upper, middle, lower, and side, the D values are 0.6, 0.7, 0.4, and 0.5, and the V values are 10, 8.5, 13, and 11.5. The gas concentration cloud maps at the heading of the working face and the concentration and wind speed variation curves along the tunnel under stable tunnel airflow conditions are shown in Figures 13 and 14.

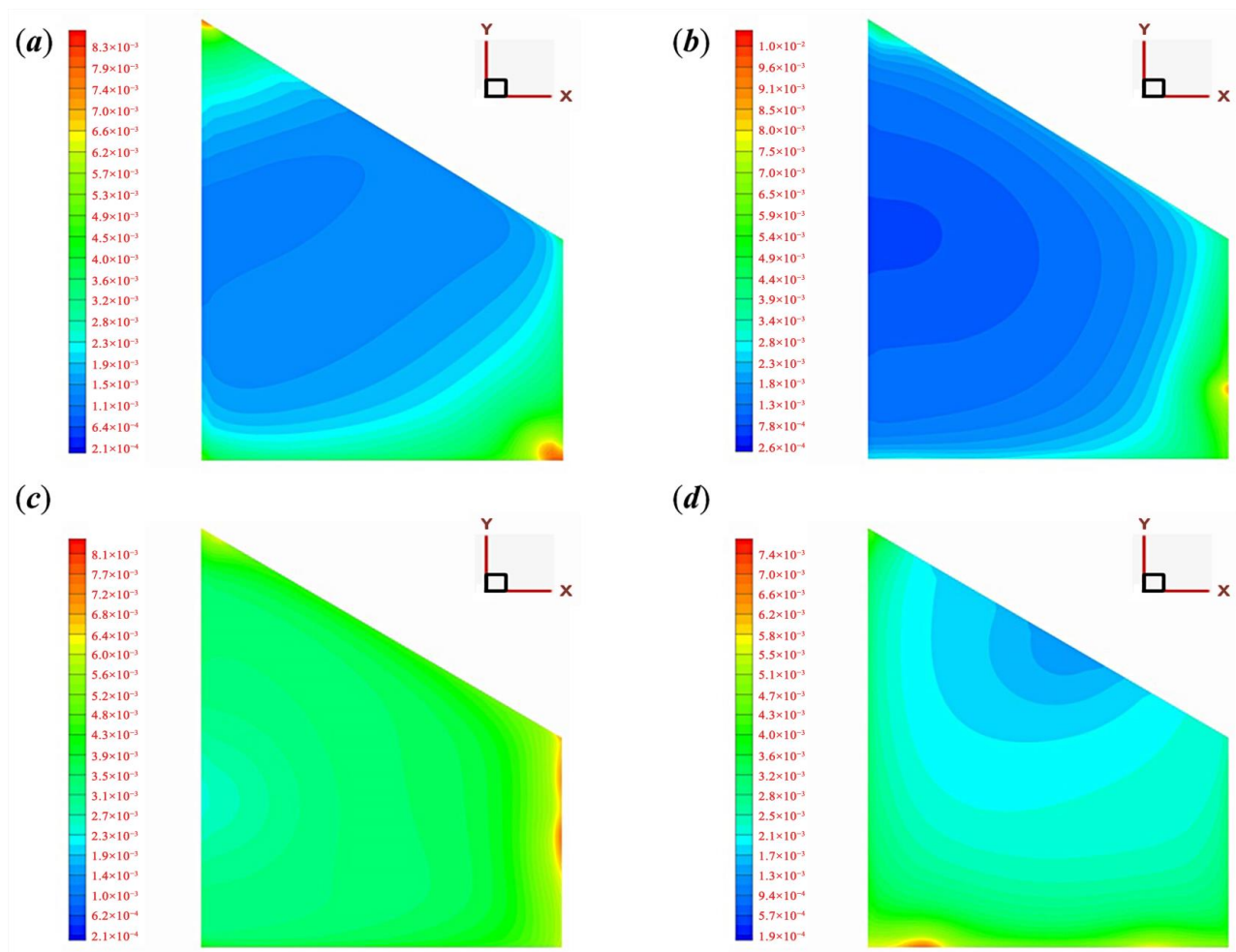


Figure 13. Gas concentration cloud of the roadway face for experiments 5–8. (a) experiments 5; (b) experiments 6; (c) experiments 7; (d) experiments 8.

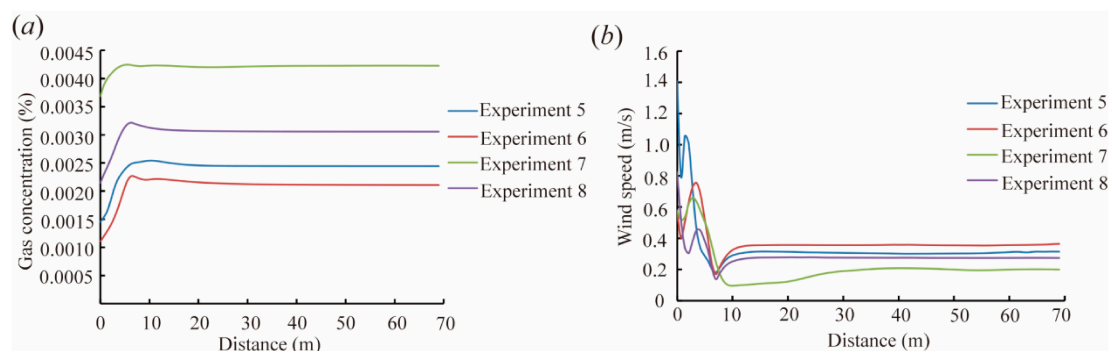


Figure 14. (a) Gas concentration variation and velocity variation curves along the tunnel for experiments 5–8; (b) Wind speed variation curves along the tunnel for experiments 5–8.

The four cloud maps labeled as (a), (b), (c), and (d) in Figure 13 represent the gas concentration distribution at the working face for the simulated results of experiments 5 to 8. From Figure 13, it can be observed that there is a noticeable stratification of gas concentration in the tunnel cross-section. Due to the ventilation duct being closer to the working face, the stratification phenomenon of gas concentration in the cross-section is more pronounced. Gas concentration at various corners of the tunnel cross-section is higher than the concentration at the center of the tunnel, indicating that gas tends to accumulate in the corners of the tunnel. Similarly, due to different positions of the ventilation duct,

the accumulation of gas concentration in the tunnel cross-section varies, with the gas concentration primarily distributed on the side away from the ventilation duct.

According to Figure 14, due to the eddy-current effect near the heading of the working face, the gas concentration and wind speed in the tunnel undergo certain changes near the working face. Meanwhile, the flow field away from the heading of the working face tends to stabilize. From both figures, it can be observed that higher wind speed corresponds to lower gas concentration. Gas concentration and wind speed exhibit a negative correlation, where higher gas concentration corresponds to lower wind speed, and both values tend to stabilize. The stable values of gas concentration for experiments 5 to 8 are 0.2443, 0.2109, 0.4229, and 0.3058, while the stable values of wind speed are 0.3074, 0.3567, 0.2020, and 0.2743, respectively.

(3) Experiments 9 to 12

For experiments 9 to 12, the values for L are all 6 m, the H positions are respectively upper, middle, lower, and side, the D values are 0.5, 0.4, 0.7, and 0.6, and the V values are 8.5, 10, 11.5, and 13. The gas concentration cloud maps at the heading of the working face and the concentration and wind speed variation curves along the tunnel under stable tunnel airflow conditions are shown in Figures 15 and 16.

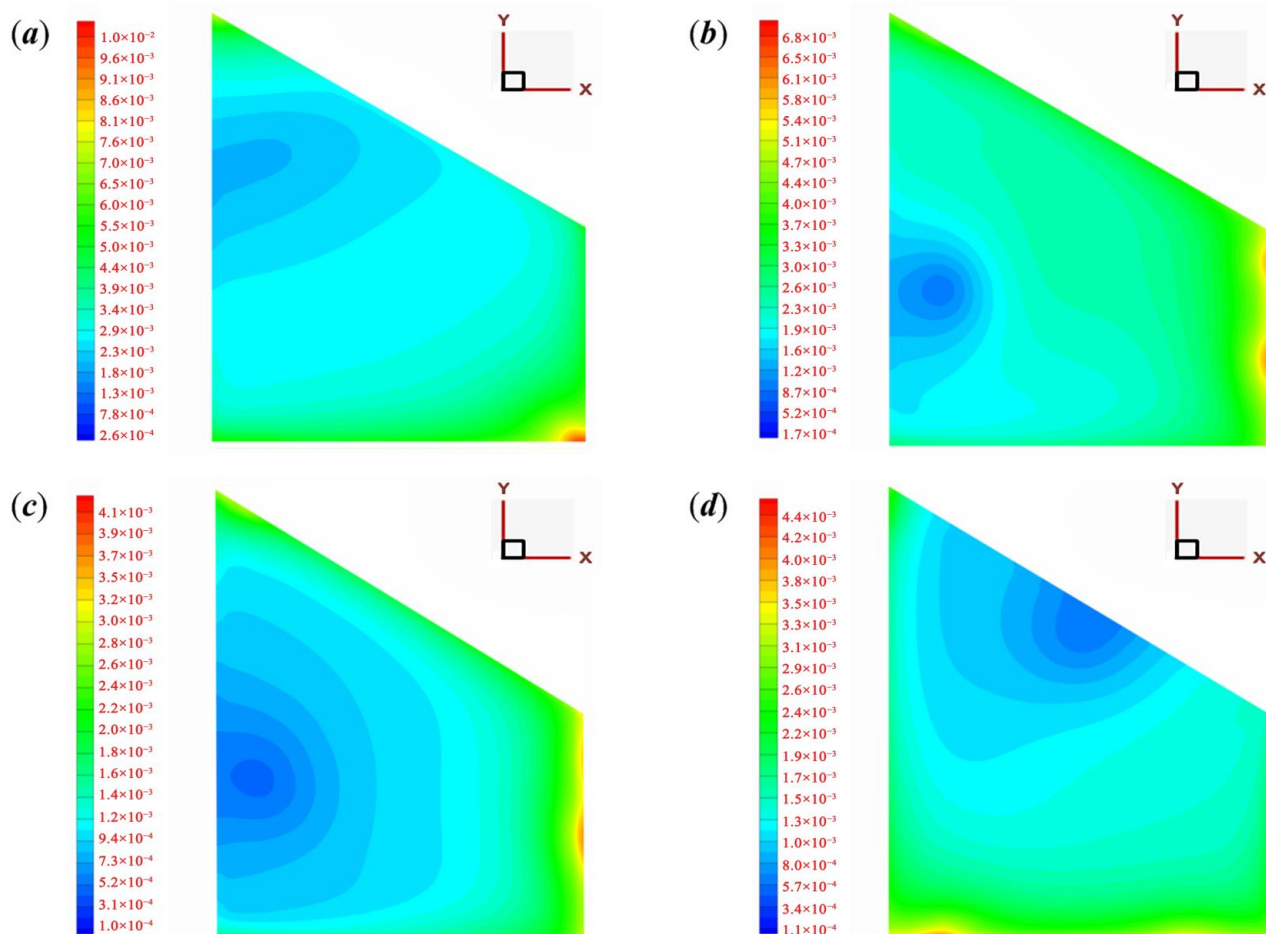


Figure 15. Gas concentration cloud of the roadway face for experiments 9–12. (a) experiments 9; (b) experiments 10; (c) experiments 11; (d) experiments 12.

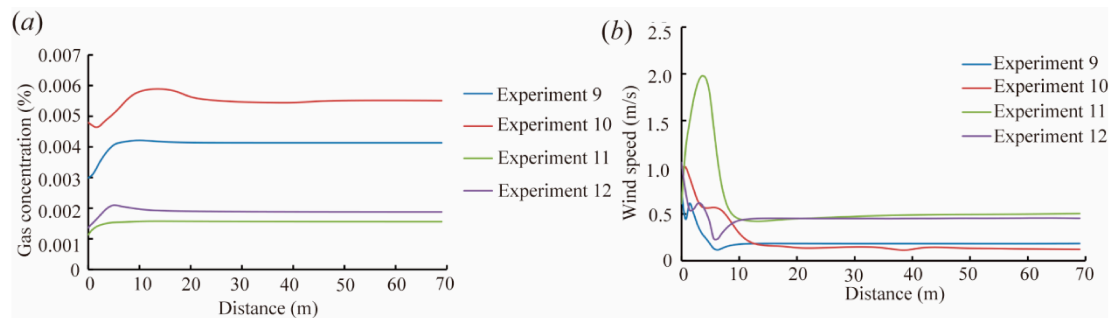


Figure 16. (a) Gas concentration variation and velocity variation curves along the tunnel for experiments 9–12; (b) Wind speed variation curves along the tunnel for experiments 9–12.

The four cloud maps labeled as (a), (b), (c), and (d) in Figure 15 represent the gas concentration distribution at the working face for the simulated results of experiments 9 to 12. From the figure, it can be observed that there is a pronounced stratification of gas concentration in the tunnel cross-section, and the stratification effect is more pronounced than in the previous two groups. This is due to the ventilation duct being closer to the working face, making the stratification phenomenon of gas concentration in the cross-section more evident. Gas concentration at various corners of the tunnel cross-section is higher than that at the center of the tunnel. Similarly, due to different positions of the ventilation duct, the accumulation of gas concentration in the tunnel cross-section varies, with the gas concentration primarily distributed on the side away from the ventilation duct. Through comparison with the cloud maps from experiments 1 to 8 (Figure 11) and experiments 5 to 8 (Figure 13), it can be observed that the size of gas concentration in the tunnel cross-section varies due to parameter changes, and the variations in the (a) and (d) cloud maps are more pronounced than those in the (c) and (d) cloud maps.

According to Figure 16, the gas concentration and velocity variation curves along the tunnel for experiments 9 to 12 follow the same trend as those for experiments 1 to 8. From the figure, it can be observed that higher wind speed corresponds to lower gas concentration. Gas concentration and wind speed exhibit a negative correlation, where higher concentration corresponds to lower wind speed, and both values tend to stabilize. The stable values of gas concentration for experiments 9 to 12 are 0.4133, 0.5513, 0.1561, and 0.1878, while the stable values of wind speed are 0.1840, 0.1320, 0.4984, and 0.4552, respectively.

(4) Experiments 13 to 16

For experiments 13 to 16, the values for L are all 5 m, the H positions are respectively upper, middle, lower, and side, the D values are 0.4, 0.5, 0.6, and 0.7, and the V values are 11.5, 13, 8.5, and 10. The gas concentration cloud maps at the heading of the working face and the concentration and wind speed variation curves along the tunnel under stable tunnel airflow conditions are shown in Figures 17 and 18.

The four cloud maps labeled as (a), (b), (c), and (d) in Figure 17 represent the gas concentration distribution at the working face for the simulated results of experiments 13 to 16. From the figure, it can be observed that there is a noticeable stratification of gas concentration in the tunnel cross-section. The gas concentration at various corners of the tunnel cross-section is higher than that at other locations in the tunnel. Similarly, due to the different positions of the ventilation duct, the accumulation of gas concentration in the tunnel cross-section varies, with the gas concentration primarily distributed on the side away from the ventilation duct. Through comparison with the cloud maps from experiments 1 to 8 (Figure 11), experiments 5 to 8 (Figure 13), and experiments 9 to 12 (Figure 15), it can be observed that changes in parameters lead to variations in the size

of gas concentration in the tunnel cross-section, and the changes in the gas concentration cloud maps of (a) and (d) are relatively more pronounced than those of (c) and (d).

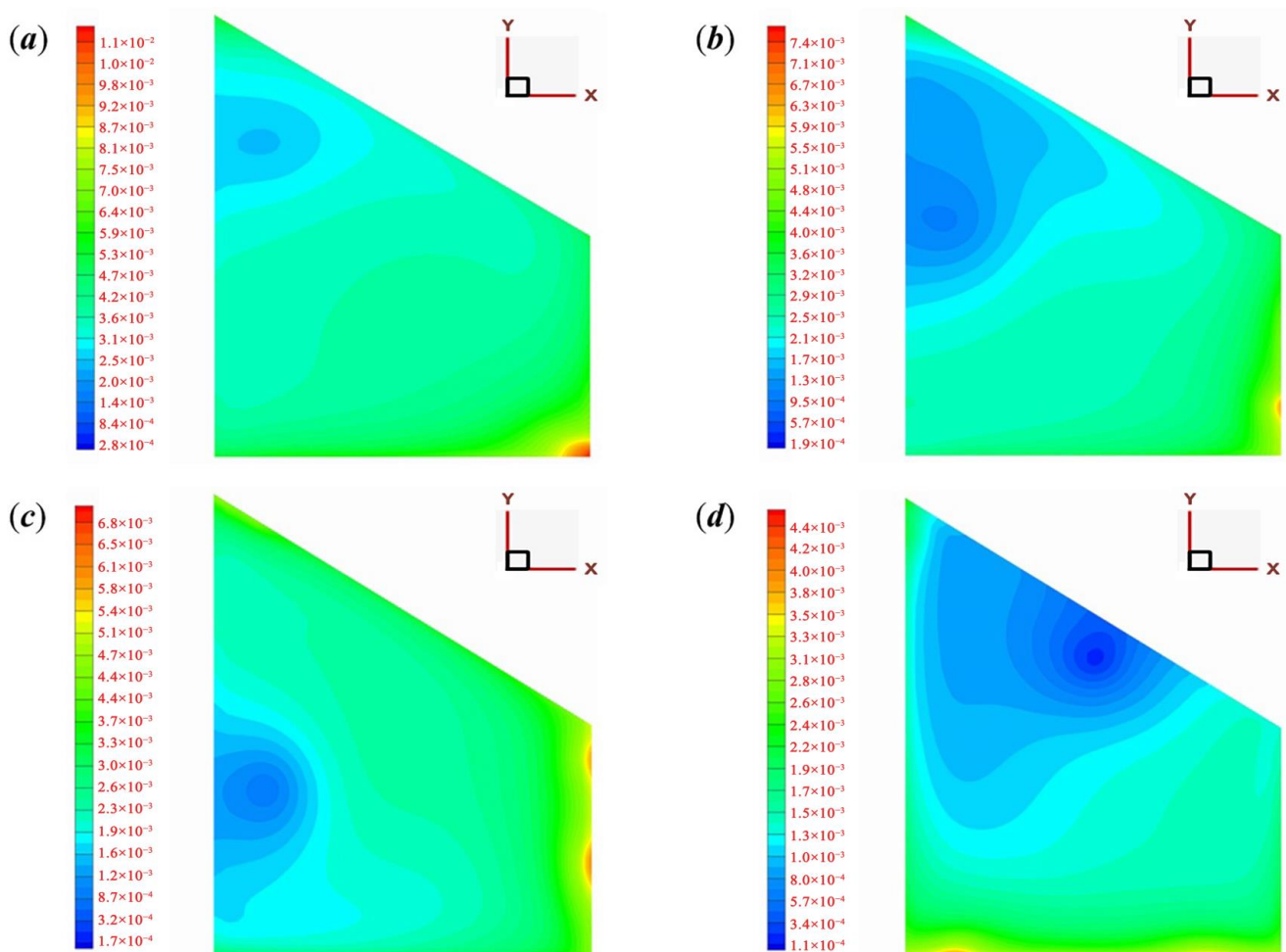


Figure 17. Gas concentration cloud of the roadway face for experiments 13–16. (a) experiments 13; (b) experiments 14; (c) experiments 15; (d) experiments 16.

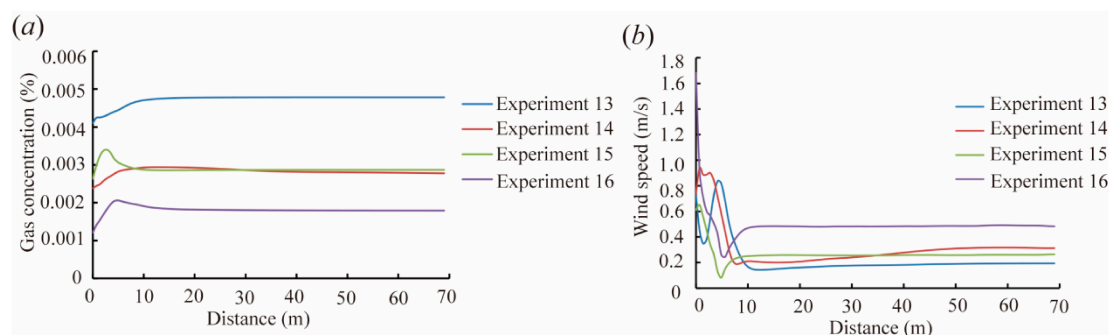


Figure 18. (a) Gas concentration variation and velocity variation curves along the tunnel for experiments 13–16; (b) Wind speed variation curves along the tunnel for experiments 13–16.

According to Figure 18, the gas concentration and velocity variation curves along the tunnel for experiments 13 to 16 generally maintain a consistent trend with those for experiments 1 to 12. From the figure, it can be observed that higher wind speed corresponds to lower gas concentration. Gas concentration and wind speed exhibit a negative correlation, where higher concentration corresponds to lower wind speed, and both values tend to stabilize. The stable values of gas concentration for experiments 13 to 16 are 0.4786, 0.2792,

0.2868, and 0.1793, while the stable values of wind speed are 0.1920, 0.3135, 0.2595, and 0.4877, respectively.

4.2. Optimal Ventilation Arrangement and Verification

4.2.1. Range Analysis

Through range analysis, the primary and secondary order of each factor is determined, identifying the most significant and less significant factors. This helps assess the degree of impact of factors on the experimental indicators, analyze the relationship between factors and experimental indicators, understand the patterns and trends of indicators as factors change, and provide guidance for further experiments. Ultimately, it leads to the identification of optimal levels for experimental factors and the optimal combinations within the experimental scope. By analyzing the simulation results of the 16 experiments conducted using the orthogonal design, the results are now compiled into the orthogonal results analysis shown in Table 4.

Table 4. Results of the orthogonal test.

Experimental Number	L/m	H/m	D/m	V/m/s	Experimental Results	
					Concentration/%	Wind Speed/m/s
1	A1	B1	C1	D1	0.1385	0.5617
2	A1	B2	C2	D2	0.2125	0.3587
3	A1	B3	C3	D3	0.3515	0.2125
4	A1	B4	C4	D4	0.6464	0.1428
5	A2	B1	C2	D3	0.2443	0.3074
6	A2	B2	C1	D4	0.2109	0.3567
7	A2	B3	C4	D1	0.4229	0.2020
8	A2	B4	C3	D2	0.3058	0.2743
9	A3	B1	C3	D4	0.4133	0.1840
10	A3	B2	C4	D3	0.5513	0.1320
11	A3	B3	C1	D2	0.1561	0.4984
12	A3	B4	C2	D1	0.1878	0.4552
13	A4	B1	C4	D2	0.4786	0.1920
14	A4	B2	C3	D1	0.2792	0.3135
15	A4	B3	C2	D4	0.2868	0.2595
16	A4	B4	C1	D3	0.1793	0.4877

According to the orthogonal experimental results, when gas concentration increases, the corresponding wind speed decreases, and vice versa. Therefore, gas concentration is chosen as the evaluation indicator for the orthogonal experiments.

The range value represents the difference between the maximum and minimum values among the average values at each level. If the range value of a factor is the largest, it indicates that this factor has the most significant impact on the indicator and is the most important factor. Conversely, it is a less significant factor. The calculation process for K_{jm} , $\bar{K}_{jm}$, and the range R_j is shown in Table 5.

Table 5. The calculation range of the heading face gas concentration value.

Name	L/m	H/m	D/m	V/m/s
K_{j1}	1.349	1.275	0.685	1.028
K_{j2}	1.184	1.254	0.931	1.153
K_{j3}	1.309	1.217	1.350	1.326
K_{j4}	1.224	1.319	2.099	1.557
$\bar{K}_{j1}$	0.337	0.319	0.171	0.257
$\bar{K}_{j2}$	0.296	0.313	0.233	0.288
$\bar{K}_{j3}$	0.327	0.304	0.337	0.332

Table 5. Cont.

Name	L/m	H/m	D/m	V/m/s
$\overline{K_{j4}}$	0.306	0.330	0.525	0.389
R_j	0.041	0.026	0.354	0.132

K_{jm} in the table represents the sum of gas concentration test indexes corresponding to the m level of factors in column j , and $\overline{K_{jm}}$ is the average value of K_{jm} . The optimal level and combination of factors in column j can be judged by the size of $\overline{K_{jm}}$. R_j is the range of the factors in column j , which reflects the change amplitude of the test index when the level of the factors in column j fluctuates.

Based on the magnitude of R_j , the impact degrees are ranked, resulting in the importance ranking of factors affecting the gas concentration at the working face of the single-heading tunnel as follows: Ventilation duct diameter (D) > Ventilation duct speed (V) > Distance from the ventilation duct outlet to the working face (L) > Suspension position of the ventilation duct (H). The gas concentration range distribution map for the single-heading tunnel is depicted in Figure 19.

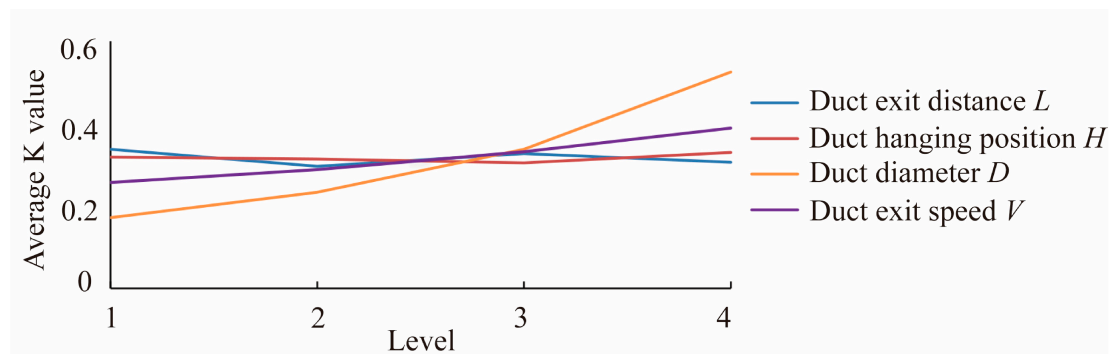


Figure 19. Heading face gas concentration distribution range.

From Figure 19, it can be observed that, under the four levels, the factor with the greatest magnitude of variation is the ventilation duct diameter, indicating the highest impact on gas concentration. Following this, the ventilation duct outlet speed has a significant impact on gas concentration. As for the factors of the distance from the ventilation duct outlet and the suspension position of the ventilation duct, their impact on gas concentration is approximately the same, with a relatively smooth variation.

4.2.2. Optimal Ventilation Arrangement

Combining the analysis from Table 5 and Figure 19, it can be determined that the ventilation duct diameter has the greatest impact on gas concentration. When the ventilation duct diameter is at the first level, the gas concentration in the single-heading tunnel reaches the minimum; when it is at the fourth level, the gas concentration reaches the maximum. The influence of the ventilation duct outlet speed on the gas concentration in the single-heading tunnel is the second most significant. As the wind speed at the ventilation duct outlet increases, the gas concentration decreases. The minimum gas concentration occurs at the first level of wind speed, while the maximum gas concentration occurs at the fourth level.

The impact of the distance from the ventilation duct outlet to the working face and the suspension position of the ventilation duct on gas concentration is nearly identical and is both less than the impact of the ventilation duct diameter and speed on gas concentration. For the factor of the distance from the ventilation duct outlet to the working face, the

gas concentration reaches its minimum at the second level. The factor of the suspension position of the ventilation duct results in the minimum gas concentration at the third level.

In summary, the optimized ventilation duct arrangement is A2, B3, C1, D1. This corresponds to a ventilation duct diameter of 0.8 m, a ventilation duct outlet speed of 13 m/s, a distance from the ventilation duct outlet to the working face of 7 m, and the ventilation duct being suspended in the lower part of the tunnel. With this configuration, the air quality in the tunnel is optimal, and the gas concentration is expected to be minimized.

4.2.3. Verification of the Optimal Ventilation Arrangement

The optimal ventilation arrangement based on the range analysis of the orthogonal experimental results is determined to be A2, B3, C1, D1. Through numerical simulations of the experimental scheme designed for the optimal ventilation arrangement, gas concentration distribution maps in the tunnel under stable airflow and the concentration variation curves along the tunnel are obtained, as shown in Figures 20 and 21.

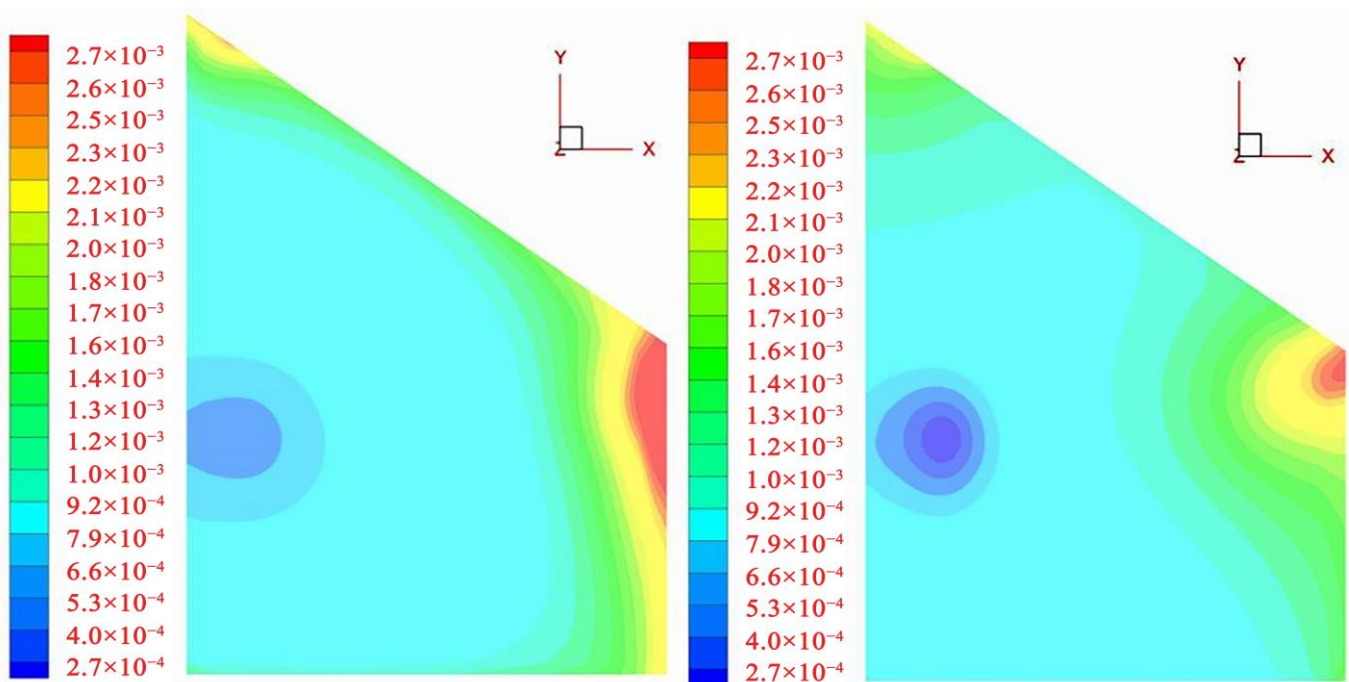


Figure 20. Gas concentration cloud in the optimal arrangement of the air duct.

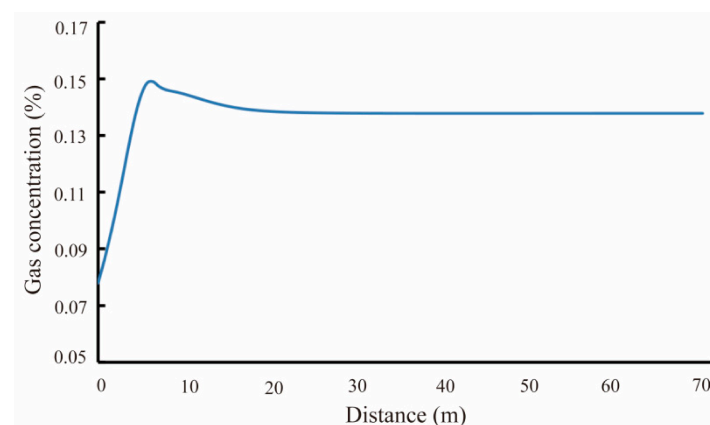


Figure 21. Gas concentration distribution curve in the optimal arrangement of the air duct.

Figure 20 represents the gas concentration distribution map under the optimal ventilation arrangement design. From the graph, it can be observed that the maximum gas

concentration in the tunnel cross-section is 0.27%, and it is evident that this concentration is higher than those in the other 16 orthogonal experimental groups. The maximum concentration is located at various corners of the tunnel cross-section, especially at the upper corner. Figure 21 shows that the stable value of gas concentration is 0.1378%, which is still the smallest when compared to the results of the 16 orthogonal experiments. Therefore, based on Figures 20 and 21, it can be concluded that the optimal ventilation arrangement design is reasonable and can be adopted for tunnel ventilation.

5. Conclusions

This study focuses on a practical engineering coal mine tunnel, and through the analysis of relevant literature, theoretical methods, and numerical software simulation, it optimizes the construction ventilation flow field and ventilation arrangement of the single-heading tunnel. The main conclusions are as follows:

- (1) The tunnel airflow field exhibits distinct characteristics of a wall-attached non-free jet. There are jet zones, recirculation zones, and vortex zones from the outlet to the heading area, consistent with existing research results.
- (2) Gas concentration variations and airflow velocity both exhibit significant layering and uneven distribution. The gas concentration on the return side of the tunnel is higher than that on the intake side, and elevated gas concentrations are observed at the upper corner and the lower-right corner on the return side. Therefore, for gas control in similar projects, monitoring should not only be strengthened at the upper corner but also extended to the lower-right corner on the return side, from the floor to the ceiling.
- (3) After analyzing and validating the simulation results against measured data, orthogonal experiments and range analysis were employed to study four major influencing factors. The impact factors on the gas concentration in the single-heading tunnel were determined as follows: duct diameter > duct outlet velocity > distance from duct outlet to heading > duct suspension position. The optimal ventilation arrangement was obtained as follows: a duct diameter of 0.7 m, a duct outlet velocity of 13 m/s (without considering a fixed air volume), a distance from duct outlet to heading of 7 m, and the duct being suspended in the middle-lower part of the tunnel. Through simulation verification of the feasibility of this optimal ventilation arrangement, the simulation results show that the gas concentration on the working face is minimized, with a stable gas concentration of 0.1378%. Therefore, the feasibility of this optimal ventilation design scheme is confirmed.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Guangli Huang and Zhen Wang were employed by the China Coal Technology and Engineering Group Chongqing Research Institute. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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