Study on the distribution law of airflow velocity in rectangular and semicircular roadway sections

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Abstract
Reliable ventilation is the cornerstone of safe production in coal mines, and accurate monitoring of ventilation parameters is the fundamental guarantee of ventilation technology decision-making. To improve the accuracy of airflow velocity monitoring in coal mine roadways, theoretical analysis, numerical simulation, and field tests were utilized to study the distribution law of airflow velocity in typical roadway sections. First, the calculation model of position of mean airflow velocity line in rectangular and semicircular arch roadway is established based on Boussinesq theory and Pelant turbulence theory. Then, to verify the correctness of the theoretical model, 25 groups of numerical simulation tests were conducted by using COMSOL-Multiphysics 3.5a software. The errors between theoretical analysis and numerical simulation are all less than 4%. In addition, the numerical results also show that the contour line of airflow velocity in roadway section is consistent with the shape of roadway section, and the isoline of airflow velocity is basically parallel to the roadway wall. In addition, the closer to the roadway wall, the denser the airflow velocity isoline, indicating that the airflow velocity gradient near the wall is larger. And the thickness of the boundary layer decreases with the increase of airflow inlet velocity. Finally, field tests have been conducted in Chongqing Research Institute and Sima Coal Mine to further verify the correctness of the calculation model and numerical simulation results. The measured distribution law of airflow velocity is consistent with the numerical simulation. And the errors between theoretical analysis and field tests are all less than 4%.

KEYWORDS
airflow velocity distribution, airflow velocity gradient, coal mine ventilation, mean airflow velocity line
1 | INTRODUCTION

Coal mine safety has always been one of the most important parts in coal mine production.1–3 With the gradual increase of mining depth, the possibility of coal mine disasters increases, which seriously threatens the production safety of coal mines.4–6 A reasonable and reliable ventilation system is the guarantee of underground safety production.7–9 In the actual ventilation situation in the coal mine, the air flow is turbulent.10 The time-averaged air velocity distribution in the roadway section is uneven, that is, the airflow velocity at a point in the roadway section is related to the spatial position, so the airflow velocity sensor arranged at different positions may have different monitoring data. To accurately obtain the mean airflow velocity of the roadway according to the airflow velocity monitoring value of a certain point in the roadway, the field experiments or simulation research must be carried out to analyze and determine the reasonable suspension position of the airflow velocity sensor and the correction formula of the average airflow velocity monitoring.11 Therefore, the accurate value of the mean airflow velocity in the roadway can be obtained through studying the velocity distribution of the air flow in the roadway, which is of great significance for the accurate calculation of the air volume and the reasonable distribution of the air volume for the coal mine.12,13

According to the field test results, Luo et al.14,15 studied the distribution of airflow in four rectangular section roadways with different supporting methods, and the results show that low airflow velocity region increases with surface roughness of the roof and wall. The high airflow velocity region was located around the floor of the roadway with rough roof and wall. However, in the roadways with smooth roof and wall, the high airflow velocity region was located around the center of section. To improve the accuracy of simulation results of mine ventilation, Janus and Krawczyk16 applied the simultaneous multi-point measurements method in the field measuring airflow velocity distribution of tunnel cross-section, and introduced the SAS turbulence model into numerical modeling. Hu et al.17 utilized the numerical modeling study the influence of wall surface roughness on the cross-sectional airflow distribution in roadway, and the results show that the influence of wall roughness on airflow velocity distribution can be reduced when the wall roughness value is less than 0.1 m. The noncontact Laser Doppler Velocimeter (LDA) is used to carry out experimental tests, and combined with numerical simulation, the stable flow of straight roadways and the airflow state after sudden expansion of sections are studied by Liu et al.18–20 The results show that the airflow velocity in roadway shows turbulent characteristics, and the velocity vector and its direction display a normal Gaussian distribution. And a large eddy can be formed in the sudden enlarged area with highly irregular airflow fluctuating around 0.1–0.2 m/s. Li et al.21 pointed out that the relation between the airflow velocity at any point (except viscous bottom) of the tube section and mean airflow velocity is nonlinear when the airflow is fully developed turbulent. However, when the mean air velocity is within a range of 0.78–6.2 m/s, and the former is proportional to the latter. Field tests carried out by Zhang22 demonstrated that the logarithmic distribution formula can ideally describe the variation law of the airflow velocity field of the roadway section. Experiments conducted by Li et al.23 indicated that the trend of airflow variation in the same roadway cross-section had nothing to do with the airflow velocity, and the airflow velocity decreased gradually along the central line of the roadway to the roadway wall. Wei et al.24 put forward a method for accurate monitoring the tunnel airflow velocity by large-span ultrasonic linear airflow velocity sensor based on the method of the time forward a method for accurate monitoring the tunnel airflow velocity distribution formula can ideally describe the variation law of the airflow velocity field of the roadway section. Experiments conducted by Li et al.23 indicated that the trend of airflow variation in the same roadway cross-section had nothing to do with the airflow velocity, and the airflow velocity decreased gradually along the central line of the roadway to the roadway wall. Wei et al.24 put forward a method for accurate monitoring the tunnel airflow velocity by large-span ultrasonic linear airflow velocity sensor based on the method of the time difference, and studied the distribution rules of section airflow velocity in rectangular tunnel with various support forms. Ligeza et al.25 established a three-dimensional modeling of the structure of flow parameter fields in mine drifts, and obtained a set of data describing the parameters of flow in real transverse sections. To calibrate different types of anemometers in a low-speed range (0.2–1.25 m/s), Pezzotti et al.26 built and characterized a wind tunnel. The wind tunnel calibration was performed by means of comparison of airspeed at the test cross-section (low-speed) and at the reference cross-section (high-speed). Based on the experimental and numerical results, combined with previous studies, Luo and Zhao27 obtained the equation which can describe the airflow velocity distribution for the three types of coal mine tunnels taking into account the influence of central airflow velocity. Zhou et al.28 studied the correction factors which is employed to convert a measured centerline air velocity to the mean air velocity using three measuring methods including single-point reading, moving traverse, and fixed-point traverse.

At present, there are few theoretical studies on the location of the mean airflow velocity in the roadway section. Through the combination of various research methods, it is only concluded that the mean airflow velocity line is a fixed position in the section, but the specific location has not been theoretically deduced. The installation position of airflow velocity monitoring sensor lacks theoretical basis in the roadway section, and the monitoring data is difficult to truly reflect the real airflow velocity of the sensor installation site, resulting in low monitoring effectiveness.
In this paper, the distribution law of airflow velocity in typical roadway sections is studied by different research methods. First, a mathematical model of the relationship between the mean airflow velocity line and the distance between the two sides of the roadway or the roof and floor in different types of roadway sections was established. And the numerical simulation, field test and other methods are used to verify the correctness of the model. The technical roadmap of this study is shown in Figure 1. This study is of great significance to improve the accuracy and access speed of ventilation parameters such as airflow velocity and air volume.

2 | THE MODEL OF THE RELATIONSHIP BETWEEN THE MEAN AIRFLOW VELOCITY LINE AND THE DISTANCE OF ROADWAY WALLS

Currently, airflow velocity monitoring is based primarily on point monitoring, and the layout of monitoring points in roadway section mainly relies on experience, which lacks theoretical basis. In this section, the theoretical model of the position of the mean airflow velocity line in the cross section of the rectangular and semicircular arch roadway is established, and the position relationship between the mean airflow velocity line and the roadway wall is obtained, which provides a theoretical basis for the accurate and rapid determination of the mean airflow velocity.

2.1 | Analysis of airflow movement characteristics in roadway

The flow state of airflow in shaft and roadway can be divided into two kinds, namely laminar flow and turbulent flow.

In coal mine ventilation, a dimensionless coefficient (Reynolds number) is usually used to distinguish the flow state of the fluid, and the dimensionless coefficient is expressed by \( Re \). When the roadway section is circular, there are\(^{29}\):

\[
Re = \frac{vd}{\nu},
\]

where \( v \) is the mean airflow velocity in the cross-section of shaft and roadway, m/s; \( \nu \) is the coefficient of viscosity of airflow, m\(^2\)/s; \( d \) is the pipe diameter, m.

In the case of noncircular roadway section, the Reynolds number formula is as follows\(^{29}\):
\[ \Re = \frac{4\nu S}{vU}, \]  

(2)

where \( S \) is the cross-sectional area of roadway, \( m^2 \); \( U \) is the perimeter of roadway section, \( m \).

In general, laminar flow occurs when the Reynolds number \( \Re \) is less than 2000, and the turbulent flow occurs when the Reynolds number \( \Re \) is greater than 4000. When the Reynolds number \( \Re \) ranges from 2000 to 4000, the flow may be laminar or turbulent.

The flow state of airflow in the underground roadway of can be judged according to the specific conditions. Supposing that the cross-sectional area of a roadway is rectangular, and the size is 5 m \( \times \) 3.2 m, the area is \( S = 16 \text{ m}^2 \), the perimeter of the section is \( U = 16.4 \text{ m} \), and the viscosity coefficient of air flow is \( \nu = 14.4 \times 10^{-6} \text{ m}^2/\text{s} \).

According to Formula (2), the results are as follows:\(^{29}\):

\[ v = \frac{vUR_x}{4S}. \]  

(3)

By substituting the above parameters into the formula, it can be calculated that when the cross-sectional area of the roadway is 16 m\(^2\), the mean airflow velocity of the transition from laminar flow to turbulent flow in the roadway is 0.009 m/s, that is, when the airflow velocity in the roadway is below 0.009 m/s, the airflow in the roadway is laminar flow; and when the airflow velocity is greater than 0.009 m/s, it is turbulent. The Coal Mine Safety Regulation requires that the airflow velocity in underground roadway and semi-coal-rock roadway should be not less than 0.25 m/s, and that of rock roadway should be not less than 0.15 m/s, much more than 0.009 m/s, so the airflow in most coal mines roadways is not in laminar state but in turbulent state.

This indicates that the airflow in all ventilation roadways in coal mines are normally in turbulent state.

2.2 | Main controlling factors of airflow velocity distribution in the roadway

According to the knowledge of fluid mechanics, combined with the airflow velocity distribution function and the mean airflow velocity calculation formula, it can be concluded that the airflow velocity distribution in roadway is mainly controlled by the frictional resistance coefficient of roadway \( \alpha \), the distance between the measuring point and the center line of the roadway \( r \), and the shape and size of the roadway section. The frictional resistance coefficient \( \alpha \) of the roadway is as follows:\(^{30}\):

\[ \alpha = \frac{\lambda \cdot \rho}{8}, \]  

(4)

where \( \rho \) is the air density, \( \text{kg/m}^3 \); \( \lambda \) is friction coefficient, and their values are measured by experiments. In the laminar flow region, \( \lambda \) is independent of the relative roughness \( \varepsilon/r \), but only related to the Reynolds number \( \Re \), and \( \lambda = 64/\Re \); while in the resistance square region, \( \lambda \) is independent of the Reynolds number \( \Re \), but only related to the relative roughness. The \( \Re \) value of the airflow in most ventilation roadways in coal mine is much greater than 4000 (the airflow is in a state of complete turbulence), and in this area:\(^{30}\):

\[ \lambda = 1 \left(\frac{1}{1.74 + 2 \log \varepsilon r^2}\right)^2, \]  

(5)

where \( r \) is the equivalent pipe diameter of roadway, \( \text{m} \), which is related to the shape and size of the roadway; \( \varepsilon \) is the absolute roughness of roadway wall, \( \text{m} \), which is related to the support form and forming condition of roadway.

This shows that the friction resistance coefficient is related to air density, roadway roughness, roadway section shape and roadway section size. The airflow velocity of a certain point in the roadway is related to the inlet air volume. In addition, in the field, the belt conveyor, air duct and various pipes placed in the roadway will have an impact on the airflow velocity distribution in the roadway.

2.3 | Theoretical analysis of the position of the mean airflow velocity line in roadway

2.3.1 | The position of mean airflow velocity line in rectangular section

According to the general expression of airflow velocity at any point in roadway section obtained by Boussinesq theory and Prandtl turbulence theory, and based on the symmetrical relation of airflow velocity distribution in rectangular roadway, the calculation formula of air volume in rectangular cross-section is obtained by integral method, and the expression of the mean airflow velocity can be determined, and then the position relation function between the position of the mean airflow velocity line and the roadway wall can be obtained.

As shown in Figure 2, a calculation model of airflow velocity distribution in rectangular roadway is established.
To ensure that the calculation model is solvable, the established model is based on the following assumptions:

1. It is assumed that the airflow in the cross section of the rectangular roadway is stable and there are no sundries in the roadway.
2. The edge effect of airflow velocity distribution in cross section is ignored.
3. The isoline of airflow velocity in the roadway is parallel to the roadway wall.
4. The parameters such as air density, temperature, and humidity in the roadway are equal everywhere in the cross section.

Based on the above assumptions, the two closed dashed lines in the figure are the isoline of airflow velocity and the distance is $dy$, and the isoline of airflow velocity is parallel to the roadway wall. Based on Boussinesq theory and Prandtl turbulence theory, the expression of airflow velocity corresponding to any point $D(x,y)$ in the graph is as follows:\[\mu = \sqrt{\frac{\alpha^2}{\rho} \frac{1}{k} \ln y + C},\] (6)

where $\mu$ is airflow velocity of arbitrary point, m/s; $\bar{v}$ is the mean airflow velocity, m/s; $y$ is the distance from any flow layer to the roadway wall, m; $\alpha$ is the friction resistance coefficient; $k$ is the mixed length coefficient; $C$ is the integral constant.

In the calculation model established in Figure 2A, to facilitate the calculation of the model, the roadway section is divided into 8 identical triangles for integral calculation according to the symmetry of the airflow velocity distribution in the rectangular roadway.

The expression of air volume corresponding to $AOB$ in Figure 2A is calculated. It follows from the symmetry of rectangular roadway section that $AOB$ is similar to $ACD$, and the corresponding edges of similar triangles are proportional. It can be obtained:

$$x = a - \frac{a}{b} y.$$

In a rectangular roadway, the $Q_1$ integral expression of air volume corresponding to $\Delta AOB$ area is as follows:

$$Q_1 = \int_0^b \left( \sqrt{\frac{\alpha^2}{\rho} \frac{1}{k}} \ln y + C \right) \left( a - \frac{a}{b} y \right) dy.$$ (8)

According to the symmetry of the rectangular roadway, the air volume in a cross section of the whole rectangular roadway is 8 times that of $\Delta AOB$, then the $Q$ expression of the rectangular cross-section air volume is as follows:

$$Q = 8Q_1 = 8 \int_0^b \left( \sqrt{\frac{\alpha^2}{\rho} \frac{1}{k}} \ln y + C \right) \left( a - \frac{a}{b} y \right) dy.$$ (9)

By assuming $f = \frac{1}{k} \sqrt{\frac{\alpha^2}{\rho}}$ and simplifying Formula (9), the following formula can be obtained:

$$Q = 4afb \ln b - 6afb + 4abC.$$ (10)

From the relationship between the air volume and the cross-section area of the roadway, it can be concluded that the expression of the mean airflow velocity of the rectangular section in Figure 1A is

$$v = \frac{Q}{4ab}.$$ (11)

The following formula can be obtained by substituting Formula (10) into Formula (11):
\[ v = f \ln b - 1.5f + C. \]  

(12)

To calculate the distance expression between the mean airflow velocity line and the roof and floor, Formula (6) and Formula (11) are solved simultaneously, and it is assumed that the airflow velocity \( \mu \) at any point in the roadway is the mean airflow velocity of the roadway, then:

\[
\sqrt{2\alpha^2 \frac{1}{\rho}} \ln k + C = \sqrt{2\alpha^2 \frac{1}{\rho}} \ln b - 1.5 \sqrt{\frac{2\alpha^2}{\rho}} \frac{1}{k} + C.
\]  

(13)

The following formula can be obtained by simplifying Formula (13):

\[
\ln y = \ln b - 1.5.
\]  

(14)

The calculated expression of the distance from the mean airflow velocity line in the cross section of the rectangular roadway to the roof and floor is as follows:

\[
y = e^{\ln b - 1.5}.
\]  

(15)

The above formula is the expression of the distance from the mean airflow velocity line to the roof and floor of the roadway.

According to the symmetry of the rectangular roadway, combined with the established geometrical model Figure 2B, the calculation expression of the distance from the mean airflow velocity line of the rectangular roadway section to the left or right side of the roadway is as follows:

\[
x = e^{\ln a - 1.5}.
\]  

(16)

The above formula is the expression of the distance from the right line of the mean airflow velocity line to the right side of the roadway wall.

2.3.2 The position of mean airflow velocity line in semicircular arch section

The semicircular arch roadway section includes a rectangular part and a semicircular part directly above the rectangular cross section. The formula for calculating the distance from the mean airflow velocity line to the two sides of the roadway is the same as that to the roadway floor in the rectangular roadway. Therefore, it is only necessary to deduce the distance of the mean airflow velocity line to the roof of the semicircle part section. The top of the section profile of the semicircular arch roadway is a semicircular arc, and the diameter of the semicircle part is 2a, and the center of the circle coincides with the center of the top edge line of the rectangular part.

As shown in Figure 3, the calculation model of airflow velocity distribution in the cross section of semicircular arch roadway takes the arc vertex as the coordinate origin and establishes a Cartesian coordinate system. The black filling area in the figure is the area between two wind isolines.

The distance from the mean airflow velocity line to the roadway roof in the semicircle arch roadway section is set as \( y \), and the area element \( (dA) \) surrounded by any two adjacent isolines of airflow velocity of the semicircle arch roadway section is obtained as follows:

\[
dA = \pi (a - y)dy.
\]  

(17)

According to Boussinesq theory and Prandtl turbulence theory, the integral expression of air volume corresponding to semicircular arch roadway is established as follows:

\[
Q = \pi \int_0^a (f \ln y + C)(a - y)dy.
\]  

(18)

The Formula (17) is simplified and solved, and the expression of the corresponding air volume of the semicircular arch roadway can be obtained as follows:

\[
Q = \frac{1}{2} \pi a^2f \ln a - \frac{3}{4} \pi a^2f + \frac{1}{2} \pi a^2C.
\]  

(19)

From the relationship between the air volume and the cross-section area of the roadway, it can be concluded that the mean airflow velocity of the semicircular arch section in Figure 3 is as follows:

\[
\bar{v} = \frac{Q}{A}.
\]  

(20)
It shows that the mean airflow velocity corresponding to the semicircular arch roadway is

$$v = f \ln a - 1.5f + C. \quad (21)$$

The distance between the mean airflow velocity line in the semicircular arch roadway and the roof of the semicircular arch roadway can be calculated as follows by combining Formula (6) with Formula (21):

$$y = \alpha \ln a - 1.5^{1.5}. \quad (22)$$

The formula for calculating the distance from the mean airflow velocity line of the semicircular arch roadway section to the roof of the semicircular arch roadway profile is

$$y = \alpha \ln a - 1.5.$$ 

Based on the above analysis, combined with previous study, the air volume is mainly determined by the airflow velocity and the roadway section area. The airflow velocity is mainly affected by the ventilation resistance caused by the section shape and wall roughness of roadway. In the actual underground coal mine, the environment in a whole tunnel cannot be the same everywhere, so it is impossible to obtain the mean airflow velocity in a section of tunnel. However, in the region where the roadway deformation is small and the airflow is fully developed, the change of roadway wind resistance can be ignored, and formulas (16) and (22) can be used to determine the position of the mean airflow velocity line. Therefore, for the same type of roadway and the same friction resistance, the mean airflow velocity line can be determined by the roadway size.

### 3 | NUMERICAL SIMULATION OF AIRFLOW VELOCITY DISTRIBUTION IN ROADWAY SECTION

#### 3.1 | Numerical model

The physical process of mine ventilation can be simply described as the continuous flow and diffusion of fresh airflow through the underground roadways. The physical models of roadway with the same size field experience are established by using COMSOL-Multiphysics 3.5a.

#### 3.1.1 | Simulation scheme

According to the field measurement experience, three rectangular roadways and two semicircular arch roadways with different cross-section sizes were selected as simulation roadways. And five groups of inlet airflow velocities and two kinds of support types corresponding to roadway types are selected as initial conditions. There are a total of 25 groups of simulation tests. The simulation scheme is shown in Table 1.

#### 3.1.2 | Geometric modeling

The geometric model of this numerical simulation is shown in Figures 4 and 5.

In this section, the geometric models of rectangular and semicircular arch roadways with different section sizes are established, and the basic simulation parameters of the two kinds of roadways under different airflow velocities and different support modes are given. The length of the roadway model is 100 m. When building models, the roadway length is in the X direction, the roadway height is in the Y direction, and the roadway width is in the Z direction. From the figures, the wind speed near the inlet varies greatly, and the wind speed distribution tends to be uniform with the increase of the distance from the inlet.

#### 3.1.3 | Basic parameters setting

COMSOL-Multiphysics 3.5a software is used to simulate the airflow velocity distribution in rectangular and semicircular arch roadways with different cross-section sizes under different inlet airflow velocities and different support forms.

(1) Rectangular roadway

The specific scheme and parameters for the simulation of the airflow velocity distribution in rectangular roadways are shown in Table 2. Besides, in this simulation scheme, all the $\alpha$ value are set as 0.012, and roughness coefficient values are set as 0.5. In this table, $\nu$ is kinematic viscosity, and $Re_{DH}$ is the Reynolds number calculated with hydraulic diameter as the characteristic length, and $I$ is the turbulence intensity.
The specific scheme and parameters for the simulation of the airflow velocity distribution in semicircular arch roadways are shown in Table 3. Besides, in this simulation scheme, all the $\alpha$ values are set as 0.01, and roughness coefficient values are set as 0.5. The parameters in this table have the same meanings as those in Table 2.

### 3.1.4 Logarithmic wall function

In COMSOL-Multiphysics, to consider the wall roughness effect, the empirical relationship between velocity and wall friction is used to replace the thin boundary layer near the wall, which is called wall function. And the logarithmic wall function was used in this simulation.

The logarithmic wall function assumes that the calculation domain begins with the distance from the wall, and that the flow is parallel to the wall, and the velocity can be described by the following formula:

$$U^+ = \frac{U}{u_\tau} = \frac{1}{k} \ln \left( \frac{\delta_w}{l^+} \right) + C^+, \quad (23)$$

where $U$ is the velocity parallel to the wall; $u_\tau$ is the friction velocity; $u_\tau = \sqrt{\frac{\tau_w}{\rho}}$; $\tau_w$ is turbulent shear stress; $k$ is Karman constant, and the value is about 0.42; $C^+$ is a
universal constant for smooth wall, and its value is 5.5 when the wall is smooth. Since the wall of this study is rough, this value is 0. And $C^+$ can be modified by using scalar variable dialog box in the module. $l^*$ is the viscous length ratio, which is defined as

$$l^* = \frac{\eta}{\rho u \tau}.$$  

(24)

The distance $\delta_w$ or its equivalent $\delta w^+ = \frac{\delta w}{u^+}$ must be specified in viscous units to set the logarithmic wall function; $\eta$ is dynamic viscosity, Pa·s; $u_\tau$ is friction velocity; In this study, the roughness height is set according to different supporting methods.

### 3.2 The distribution characteristics of airflow velocity in roadway sections

According to the simulation scheme, the contours of the airflow velocity distribution in different roadway sections were simulated. To facilitate the comparative analysis, the velocity contours with three airflow inlet
velocity values of 0.8, 4.0, and 8.0 m/s is selected, as shown in Figures 6–10. In general, there will be a vortex in the airflow field at the entrance. To avoid the influence of vortex on the flow field, the cross-sections at the distance of 50 m from the roadway entrance were selected. And the airflow velocity field in the cross section remains basically unchanged and reaches a fully developed state.

From Figures 6 to 10, the contour line of airflow velocity in roadway section is consistent with the shape of roadway section, and the isoline of airflow velocity is basically parallel to the roadway wall, and the isoline of airflow velocity expands from the central part of roadway section to the roadway wall. Besides, the closer to the roadway wall, the denser the airflow velocity isoline, indicating that the airflow velocity gradient near the wall is larger. And the closer to the central line of the roadway section, the thinner the airflow velocity isoline is and the larger the air velocity is, indicating that the smaller the airflow velocity gradient is, that is, the airflow velocities in the central part of the roadway change little. In the same roadway, the greater the airflow inlet velocity is, the smaller the thickness of the near-wall velocity variation layer is, that is, the thickness of the boundary layer decreases with the increase of airflow inlet velocity.

3.3 Distribution law of airflow velocity in the central axis of roadway sections

To find out the relationship between the velocity of each point on the central axis of the roadway section and the mean airflow velocity. According to the roadway type selected by the simulation scheme, the data monitoring location is selected at the central axis of $X = 50 \text{ m}$ roadway section.

3.3.1 Analysis of airflow velocity in the central axis of roadway sections

Figures 11 and 12 show the airflow velocity distribution on the central axis of the rectangular and semicircular arch roadways with different section sizes, respectively. In the figures, $d$ is the distance from the measuring point to the roadway roof, and $v$ is the actual airflow velocity of each measuring point on the central axis. It can be seen that the airflow velocity distribution on the central axis is symmetrical with respect to the central point of the roadway section. The airflow velocity of the measuring point increases with the increase of the distance from the roof, and remains unchanged when the distance from the roof increases to a certain extent. The gradient of airflow velocity near the
FIGURE 7  The contours of airflow velocity distribution under different inlet airflow velocities in rectangular roadway (5 × 3.5 m)

FIGURE 8  The contours of airflow velocity distribution under different inlet airflow velocities in rectangular roadway (6 × 4 m)
FIGURE 9  The contours of airflow velocity distribution under different inlet airflow velocities in the semicircular arch roadway (4 × 3 m)

FIGURE 10  The contours of airflow velocity distribution under different inlet airflow velocities in semicircular arch roadway (4.5 × 3.3 m)
roadway wall is large, and the gradient of airflow velocity in the central part of the roadway section is small. This is mainly caused by the influence of the boundary layer of the roadway wall. And the thickness of the boundary layer decreases with the increase of airflow velocity.

To find out the relationship between the airflow velocity of each measuring point and the mean airflow velocity of the roadway, the nonlinear functions of airflow velocity and average airflow velocity at each measuring point are fitted by Origin 8.0, and the results are shown in Tables 4 and 5.

Tables 4 and 5 show the relationship between the airflow velocity of each measuring point and the mean airflow velocity of the rectangular and semi-circular arch roadways with different section sizes under different airflow velocities, respectively. According to the results, it can be seen that within a certain distance from the roof, there is a logarithmic relationship between the ratio of the measuring point airflow velocity to the mean airflow velocity and the distance. When the distance from the roof increases to a certain extent, the ratio of the airflow velocity of measuring point to the mean airflow velocity is constant. In addition, the ratio of maximum airflow velocity to mean airflow velocity in the roadway section decreases with the increase of mean airflow velocity. In addition, by comparison, the roadway section shape has little influence on the ratio of the maximum airflow velocity to the mean airflow velocity, but has a great influence on the airflow velocity gradient.

### 3.3.2 Comparative of numerical simulation results and theoretical model

In this section, the distances from mean airflow velocity to the roadway roof in different roadway from the numerical simulation and calculated from theoretical model are examined. The comparison results are shown in Tables 6 and 7. It can be seen that the errors between the theoretical
FIGURE 12 Distribution law of airflow velocity on the central axis of semicircular arch roadway. (A) W: 4 m, H: 3 m and (B) W: 4.5 m, H: 3.3 m.

TABLE 4 The relationship between the airflow velocity on central line and the mean airflow velocity in the rectangle roadway.

| Section sizes (m) | Mean airflow velocity (m/s) | \( \frac{v}{\overline{v}} \) |
|-------------------|-----------------------------|-----------------|
| W: 4 H: 3         |                             |                 |
|                   | 0.8                         | \( \frac{v}{\overline{v}} = 1.1839 + 0.1633 \ln d \) \( \frac{v}{\overline{v}} = 1.225 \) |
|                   | 2.0                         | \( \frac{v}{\overline{v}} = 1.1573 + 0.1391 \ln d \) \( \frac{v}{\overline{v}} = 1.21 \) |
|                   | 4.0                         | \( \frac{v}{\overline{v}} = 1.1406 + 0.1267 \ln d \) \( \frac{v}{\overline{v}} = 1.185 \) |
|                   | 6.0                         | \( \frac{v}{\overline{v}} = 1.1332 + 0.1189 \ln d \) \( \frac{v}{\overline{v}} = 1.175 \) |
|                   | 8.0                         | \( \frac{v}{\overline{v}} = 1.1273 + 0.1146 \ln d \) \( \frac{v}{\overline{v}} = 1.1663 \) |
| W: 5 H: 3.5       |                             |                 |
|                   | 0.8                         | \( \frac{v}{\overline{v}} = 1.1605 + 0.1686 \ln d \) \( \frac{v}{\overline{v}} = 1.225 \) |
|                   | 2.0                         | \( \frac{v}{\overline{v}} = 1.1179 + 0.1221 \ln d \) \( \frac{v}{\overline{v}} = 1.175 \) |
|                   | 4.0                         | \( \frac{v}{\overline{v}} = 1.1065 + 0.1113 \ln d \) \( \frac{v}{\overline{v}} = 1.1575 \) |
|                   | 6.0                         | \( \frac{v}{\overline{v}} = 1.0999 + 0.105 \ln d \) \( \frac{v}{\overline{v}} = 1.147 \) |
|                   | 8.0                         | \( \frac{v}{\overline{v}} = 1.0924 + 0.0968 \ln d \) \( \frac{v}{\overline{v}} = 1.1338 \) |
| W: 6 H: 4         |                             |                 |
|                   | 0.8                         | \( \frac{v}{\overline{v}} = 1.1171 + 0.143 \ln d \) \( \frac{v}{\overline{v}} = 1.1875 \) |
|                   | 2.0                         | \( \frac{v}{\overline{v}} = 1.0899 + 0.1084 \ln d \) \( \frac{v}{\overline{v}} = 1.155 \) |
|                   | 4.0                         | \( \frac{v}{\overline{v}} = 1.0796 + 0.0964 \ln d \) \( \frac{v}{\overline{v}} = 1.135 \) |
|                   | 6.0                         | \( \frac{v}{\overline{v}} = 1.0596 + 0.0723 \ln d \) \( \frac{v}{\overline{v}} = 1.097 \) |
|                   | 8.0                         | \( \frac{v}{\overline{v}} = 1.0718 + 0.0866 \ln d \) \( \frac{v}{\overline{v}} = 1.12 \) |
calculation results and the numerical simulation results have nothing to do with the shape of roadway section and mean airflow velocity, and they are all less than 4%. The conclusions of the two research methods are unified, which verifies the reliability of the theoretical model.

4 | VERIFICATION TESTS OF AIRFLOW VELOCITY DISTRIBUTION IN DIFFERENT ROADWAYS

In previous sections, a set of formulas for the position of the mean airflow velocity line in different roadway sections were obtained through theoretical research and numerical simulation. In this section, the reliability of the theoretical model is further verified by field tests.

4.1 | Experimental preparation

4.1.1 | Preparation of experimental equipment

(1) Data monitoring equipment

| Section sizes (m) | Mean airflow velocity (m/s) | $\frac{d}{\bar{v}}$ |
|-------------------|-----------------------------|------------------|
| W: 4 H: 3        | $d \subseteq [0, 1.25]$    | $d \subseteq [1.25, 1.5]$ |
| 0.8               | $\frac{v}{\bar{v}} = 1.173 + 0.153 \ln \frac{r}{d}$ | $\frac{v}{\bar{v}} = 1.2125$ |
| 2.0               | $\frac{v}{\bar{v}} = 1.1157 + 0.1075 \ln \frac{r}{d}$ | $\frac{v}{\bar{v}} = 1.145$ |
| 4.0               | $\frac{v}{\bar{v}} = 1.0555 + 0.0975 \ln \frac{r}{d}$ | $\frac{v}{\bar{v}} = 1.1275$ |
| 6.0               | $\frac{v}{\bar{v}} = 1.0985 + 0.092 \ln \frac{r}{d}$ | $\frac{v}{\bar{v}} = 1.118$ |
| 8.0               | $\frac{v}{\bar{v}} = 1.0941 + 0.0881 \ln \frac{r}{d}$ | $\frac{v}{\bar{v}} = 1.1113$ |

| Section sizes (m) | Mean airflow velocity (m/s) | $\frac{d}{\bar{v}}$ |
|-------------------|-----------------------------|------------------|
| W: 4.5 H: 3.3     | $d \subseteq [0, 1.6]$    | $d \subseteq [1.6, 1.65]$ |
| 0.8               | $\frac{v}{\bar{v}} = 1.1476 + 0.1473 \ln \frac{r}{d}$ | $\frac{v}{\bar{v}} = 1.2$ |
| 2.0               | $\frac{v}{\bar{v}} = 1.102 + 0.1038 \ln \frac{r}{d}$ | $\frac{v}{\bar{v}} = 1.135$ |
| 4.0               | $\frac{v}{\bar{v}} = 1.0894 + 0.0908 \ln \frac{r}{d}$ | $\frac{v}{\bar{v}} = 1.1175$ |
| 6.0               | $\frac{v}{\bar{v}} = 1.0827 + 0.084 \ln \frac{r}{d}$ | $\frac{v}{\bar{v}} = 1.107$ |
| 8.0               | $\frac{v}{\bar{v}} = 1.0793 + 0.0806 \ln \frac{r}{d}$ | $\frac{v}{\bar{v}} = 1.1012$ |

| Section sizes (m) | Mean airflow velocity (m/s) | Distance from numerical simulation $d$ (m) | Distance from theoretical model $D$ (m) | Error $\left(\frac{d-D}{D} \times 100\%\right)$ |
|-------------------|-----------------------------|-----------------------------|-----------------------------|-------------------------------|
| W: 4 H: 3         | 0.8                         | 0.3243                      | 0.3347                      | 3.11%                         |
|                   | 2.0                         | 0.3228                      | 0.3347                      | 3.57%                         |
|                   | 4.0                         | 0.3297                      | 0.3347                      | 1.51%                         |
|                   | 6.0                         | 0.3262                      | 0.3347                      | 2.54%                         |
|                   | 8.0                         | 0.3293                      | 0.3347                      | 1.62%                         |
| W: 5 H: 3.5       | 0.8                         | 0.3860                      | 0.3905                      | 1.16%                         |
|                   | 2.0                         | 0.3808                      | 0.3905                      | 2.50%                         |
|                   | 4.0                         | 0.3841                      | 0.3905                      | 1.64%                         |
|                   | 6.0                         | 0.3862                      | 0.3905                      | 1.10%                         |
|                   | 8.0                         | 0.3849                      | 0.3905                      | 1.41%                         |
| W: 6 H: 4         | 0.8                         | 0.4409                      | 0.4462                      | 1.18%                         |
|                   | 2.0                         | 0.4363                      | 0.4462                      | 2.21%                         |
|                   | 4.0                         | 0.4379                      | 0.4462                      | 1.86%                         |
|                   | 6.0                         | 0.4385                      | 0.4462                      | 1.72%                         |
|                   | 8.0                         | 0.4364                      | 0.4462                      | 2.19%                         |
In this experiment, 16 CFD15 coal mine electronic airflow velocity measuring instruments (hereinafter referred to as “anemometer”) and 16 YHC mine intrinsically safe data acquisition instruments were used. Ultrasonic electronic airflow velocity measuring instrument and data acquisition instrument are shown in Figure 13.

**TABLE 7** Comparison of theoretical model and numerical simulation results of semicircular arch roadway

| Section sizes (m) | Mean airflow velocity (m/s) | Distance from numerical simulation d (m) | Distance from theoretical model D (m) | Error ($\frac{d-D}{D} \times 100\%$) |
|-------------------|-----------------------------|----------------------------------------|--------------------------------------|----------------------------------|
| W: 4, H: 3        | 0.8                         | 0.3228                                  | 0.3347                               | 3.56%                            |
|                   | 2.0                         | 0.3286                                  | 0.3347                               | 1.84%                            |
|                   | 4.0                         | 0.3305                                  | 0.3347                               | 1.25%                            |
|                   | 6.0                         | 0.3266                                  | 0.3347                               | 2.42%                            |
|                   | 8.0                         | 0.3257                                  | 0.3347                               | 2.68%                            |
| W: 4.5, H: 3.3    | 0.8                         | 0.3671                                  | 0.3682                               | 0.29%                            |
|                   | 2.0                         | 0.3621                                  | 0.3682                               | 1.66%                            |
|                   | 4.0                         | 0.3628                                  | 0.3682                               | 1.47%                            |
|                   | 6.0                         | 0.3628                                  | 0.3682                               | 1.47%                            |
|                   | 8.0                         | 0.3625                                  | 0.3682                               | 1.54%                            |

**FIGURE 13** Anemometer and data acquisition instrument

In this experiment, 16 CFD15 coal mine electronic airflow velocity measuring instruments (hereinafter referred to as “anemometer”) and 16 YHC mine intrinsically safe data acquisition instruments were used. Ultrasonic electronic airflow velocity measuring instrument and data acquisition instrument are shown in Figure 13.

(2) Main parameters of anemometer and data acquisition instrument

The main technical specifications of the anemometer are shown in Table 8.

The ventilation parameter acquisition App is independently developed and installed on the data acquisition instrument to realize the synchronous data acquisition. The main technical specifications of the data acquisition instrument are shown in Table 9.

**TABLE 8** Main technical specifications of anemometer and data acquisition instrument

| Parameter                | Specification |
|--------------------------|---------------|
| Brand name               | ZD-200        |
| Power supply             | 9V, 2.0A      |
| Measurement range        | 0.2–20.0 m/s  |
| Temperature range        | -10°C–50°C    |
| Humidity range           | 10%–90%       |
| Measurement accuracy     | 0.1%          |

**TABLE 9** Main technical specifications of data acquisition instrument

| Parameter                | Specification |
|--------------------------|---------------|
| Brand name               | YHC500        |
| Power supply             | 9V, 2.0A      |
| Measurement range        | 0.2–20.0 m/s  |
| Temperature range        | -10°C–50°C    |
| Humidity range           | 10%–90%       |
| Measurement accuracy     | 0.1%          |

**4.1.2** Calibration of experimental instruments

(1) Calibration method

16 CFD15 anemometers are calibrated in the ground wind tunnel, as shown in Figure 14 at the national first-class wind tunnel laboratory of Chongqing Research Institute Co. Ltd., China Coal Science and Industry Group. Through the software control system, the control and adjustment of airflow velocity, the automatic collection of dynamic pressure, atmospheric pressure and temperature can be realized, and finally the standard airflow velocity can be obtained. The wind tunnel laboratory can provide the standard airflow velocity flow field with high stability and uniformity of 0.50–40.00 m/s, which can be compared with the measured anemometer.

(2) Calibration results

When adjusting the anemometer, 5 standard airflow velocities were tested in the wind tunnel, and the readings of the same tested anemometer were compared with the standard airflow velocity values under the same atmospheric pressure and the same ambient temperature. If the error is within 0.1 m/s, the test passes; Otherwise, the anemometer is debugged on the spot until it is qualified. This method is used to detect and adjust 16 anemometers in turn, and the data recorded in the calibration process are shown in Table 12. It can be seen that the absolute errors of the 16 anemometers after adjustment are all within 0.1 m/s, which meets the error requirements and can be used for field testing. The anemometer calibration data is shown in Table 10.
4.2 Field test in simulation roadway

4.2.1 Brief introduction to simulation roadway

There exists a ventilation fire test roadway system in Chongqing Research Institute (as shown in Figure 15), which is equipped with airflow draught device, fan connection device, velocity measuring station, dust measuring station, air door and air resistance regulating device. The fan used is FBCDZN№12/2 × 45. After the transformation, a complete ventilation test system is formed, and the total length of the roadway is about 460 m, as shown in Figure 14. A section of straight roadway AB with regular cross section and no debris accumulation is in the roadway. The shape of the roadway is semicircular arch, and the supporting method is Anchor jetting. The roadway is 2.82 m high, 2.89 m wide, and 50 m long, in which the length of the experimental area is 9 m, the upwind side is 12 m and the leeward side is 29 m. It meets the requirements of the measuring method of Mine Ventilation Resistance (MT/T440-2008) that the width of the roadway is three times the width of the upwind side and eight times the width of the downwind side without convergence points and air dividing points.

4.2.2 Measuring method

(1) The laser rangefinder is used to accurately measure the size of the cross section, and its support form was recorded. Before testing, the obstacles in the roadway should be cleared, so that the roadway in the whole measurement range can meet the measurement requirements.

(2) Since the semicircular arch roadway is symmetrical to the left and right, 1/2 cross section of the semicircular arch roadway is selected for the measurement. The position of the monitoring point of the cross-section is calculated according to the measured cross-section size: the anemometer is denser near the wall and sparse away from the wall. The specific values of the distance between measuring surfaces \( l \), the number of measuring surfaces \( N \), the height of measuring lines \( h \), the length of measuring lines \( L \) and the number of anemometers \( n \) of each measuring line are determined according to the cross-section size of the roadway. Then, the installation rod of the anemometer is assembled according to the length of the measuring line \( L \), the number of measuring surfaces \( N \) and the number of anemometers per line \( n \). And the anemometer is fixed on the installation rod, and the installation rod of the anemometer is fixed in the roadway according to the distance between the measuring surface \( l \) and the measuring line \( h \). The specific layout is shown in Figure 16.

(3) In this test, the fan is started with different working frequencies to create different airflow velocity conditions in the roadway. The working frequency of the fan is adjusted four times, which is 15, 20, 30, and 40 Hz. Under the four working frequencies, the
| No.       | Measuring velocity (m/s) | Standard velocity (m/s) | Error | No.       | Measuring velocity (m/s) | Standard velocity (m/s) | Error |
|-----------|-------------------------|-------------------------|-------|-----------|-------------------------|-------------------------|-------|
| 20180249  | 0.69                    | 0.61                    | 0.08  | 20180146  | 0.53                    | 0.6                      | −0.07 |
|           | 3.06                    | 3.12                    | −0.06 | 3.11      | 3.09                    | 0.02                     |       |
|           | 6.41                    | 6.47                    | −0.06 | 6.41      | 6.44                    | −0.03                    |       |
|           | 9.32                    | 9.37                    | −0.05 | 9.41      | 9.38                    | 0.03                     |       |
|           | 11.08                   | 11.13                   | −0.05 | 11.2      | 11.1                    | 0.01                     |       |
|           | 13.35                   | 13.42                   | −0.07 | 13.39     | 13.38                   | 0.01                     |       |
| 20180234  | 0.64                    | 0.6                     | 0.04  | 20180196  | 0.62                    | 0.6                      | 0.02  |
|           | 3.1                     | 3.06                    | 0.04  | 3.12      | 3.09                    | 0.03                     |       |
|           | 6.48                    | 6.46                    | 0.02  | 6.49      | 6.46                    | 0.03                     |       |
|           | 9.44                    | 9.39                    | 0.05  | 9.46      | 9.37                    | 0.09                     |       |
|           | 11.13                   | 11.11                   | 0.02  | 11.08     | 11.09                   | −0.01                    |       |
|           | 13.38                   | 13.41                   | −0.03 | 13.34     | 13.38                   | −0.04                    |       |
| 20180207  | 0.59                    | 0.6                     | −0.01 | 20180236  | 0.61                    | 0.6                      | 0.01  |
|           | 3.12                    | 3.09                    | 0.03  | 3.05      | 3.09                    | 0.04                     |       |
|           | 6.41                    | 6.46                    | −0.05 | 6.46      | 6.46                    | 0                        |       |
|           | 9.37                    | 9.37                    | 0     | 9.31      | 9.39                    | −0.08                    |       |
|           | 11.01                   | 11.07                   | −0.06 | 11.09     | 11.1                    | −0.01                    |       |
|           | 13.4                    | 13.39                   | 0.01  | 13.41     | 13.4                    | 0.01                     |       |
| 20180245  | 0.62                    | 0.6                     | 0.02  | 20180216  | 0.59                    | 0.6                      | −0.01 |
|           | 3.11                    | 3.12                    | −0.01 | 3.11      | 3.12                    | −0.01                    |       |
|           | 6.43                    | 6.44                    | −0.01 | 6.41      | 6.43                    | −0.02                    |       |
|           | 9.33                    | 9.35                    | −0.02 | 9.32      | 9.35                    | −0.03                    |       |
|           | 11.05                   | 11.1                    | 0.04  | 11.03     | 11.06                   | −0.03                    |       |
|           | 13.37                   | 13.38                   | −0.01 | 13.33     | 13.34                   | −0.01                    |       |
| 20180229  | 0.57                    | 0.6                     | −0.03 | 20180215  | 0.58                    | 0.6                      | −0.02 |
|           | 3.09                    | 3.12                    | −0.03 | 3.09      | 3.12                    | −0.03                    |       |
|           | 6.43                    | 6.42                    | 0.01  | 6.46      | 6.43                    | 0.03                     |       |
|           | 9.32                    | 9.31                    | 0.01  | 9.31      | 9.34                    | −0.03                    |       |
|           | 11.04                   | 11.05                   | −0.01 | 11.08     | 11.1                    | −0.02                    |       |
|           | 13.29                   | 13.31                   | −0.02 | 13.32     | 13.36                   | −0.04                    |       |
| 20180254  | 0.59                    | 0.6                     | −0.01 | 20180222  | 0.61                    | 0.6                      | 0.01  |
|           | 3.13                    | 3.12                    | 0.01  | 3.09      | 3.09                    | 0                        |       |
|           | 6.38                    | 6.42                    | −0.04 | 6.43      | 6.42                    | 0.01                     |       |
|           | 9.35                    | 9.34                    | 0.01  | 9.35      | 9.34                    | 0.01                     |       |
|           | 11.02                   | 11.06                   | −0.04 | 11.04     | 11.06                   | −0.02                    |       |
|           | 13.34                   | 13.34                   | 0     | 13.33     | 13.34                   | −0.01                    |       |
| 20180248  | 0.63                    | 0.6                     | 0.03  | 20180209  | 0.63                    | 0.6                      | 0.03  |
|           | 3.1                     | 3.09                    | 0.01  | 3.05      | 3.09                    | −0.04                    |       |

(Continues)
mean airflow velocity measured by the six-line wind measurement method in the experimental roadway is 1.3, 2.2, 2.6, and 3.5 m/s, respectively.

(4) A total of 16 mine intrinsically safe data collectors were used in this experiment. The ventilation parameter collector App is installed in the mine intrinsically safe data collector and connected with the monitoring anemometer one by one. To obtain the monitoring data of all anemometers at the same time, the ventilation parameter collector start time is set by modifying the built-in program of the ventilation parameter collector. All ventilation parameter collectors start up at the same time and collect the monitoring data of the anemometer. All the data acquisition instruments are opened and placed in the lower tuyere of the tested roadway, as shown in Figure 17. At the same time, another data acquisition instrument is used to take pictures and record the data, which ensures the simultaneity of the data acquisition.

### 4.2.3 Data analysis

The measured data are fitted into a curve according to the boundary conditions by using Surfer software, and the boundary points are taken every 50 mm. The results are shown in Figure 18. It can be seen that the airflow velocity isoline of the roadway section is approximately a semi-circular arch. The closer to the roadway wall, the denser the...
isoline of airflow velocity, indicating that the airflow velocity gradient is larger near the wall. And the closer to the center of the roadway, the thinner the isoline of airflow velocity is, indicating that the smaller the airflow velocity gradient is. The greater the inlet airflow velocity is, the smaller the thickness of the low velocity area near the wall is, that is, the thickness of the boundary layer with low airflow velocity decreases with the increase of airflow velocity. In the figures, the red line in the figure is the measured average airflow velocity line. When the start-up frequency of the fan in the experimental roadway is 15, 20, 30, and 40 Hz, the airflow inlet velocity is 1.3, 2, 2.6, and 3.5 m/s, and the corresponding average distance from the measured mean airflow velocity line to the roadway roof is 0.3298, 0.3274, 0.3256, and 0.3244 m, respectively.

FIGURE 16 Schematic layout of anemometer in semicircular arch roadway. (A) The position of measuring line and cross section and (B) the installation position of anemometers.

FIGURE 17 The layout of the data acquisition instruments in test roadway.
To verify the theoretical model, the average distance value $d_1$ from the measured position of the mean airflow velocity line to the roof and the distance $d_2$ from the position of the theoretical mean airflow velocity line to the roof are compared, as shown in Table 11.

It can be seen that the errors of the position the mean airflow velocity line measured in the experimental roadway and calculated by the theoretical model are both less than 5%, which indicates that the theoretical model is reliable.

### Table 11
Comparison of the field test results and theoretical results of the distance from the mean airflow velocity line to the roof

| Section type     | Section size (m × m) | Airflow velocity (m/s) | Field value $d_1$ (m) | Theoretical value (m) | Error ($\frac{d_1 - d_2}{d_2} \times 100\%$) |
|------------------|----------------------|------------------------|-----------------------|-----------------------|------------------------------------------|
| Semicircular arch| 2.89 × 2.82          | 1.3                    | 0.3298                | 0.3146                | 4.8%                                     |
|                  |                      | 2.0                    | 0.3274                | 0.3146                | 3.9%                                     |
|                  |                      | 2.6                    | 0.3256                | 0.3146                | 3.5%                                     |
|                  |                      | 3.5                    | 0.3244                | 0.3146                | 3.1%                                     |

To further verify the position of the mean airflow velocity line and the distribution law of the airflow velocity in the rectangular section, the rectangular roadway in Sima...
Coal Mine of Lu’an Group is selected as the field experimental roadway. 4 airflow velocities are selected for measurement.

4.3.1 Introduction to the test site

The partition ventilation system is adopted in Sima Coal Mine, which consists of main vertical shaft, auxiliary vertical shaft, and new air-intake shaft, central return air shaft and new return air shaft. The total air intake volume of the mine is 19578 m³/min, and the total return air volume is 19200 m³/min.

4.3.2 Experimental method

Due to the accumulation of all kinds of equipment or other obstacles in coal mines, the air flow is in an unstable state. It is difficult to measure the airflow velocity in the same section at the same time. Therefore, the mirror ladder method of is adopted to measure the airflow velocity in 100 m roadway without deformation and sundries accumulation. The specific steps for measuring airflow velocity in roadway are as follows:

(1) The laser rangefinder is used to accurately measure the size of the cross section, and its support form was recorded. Before measuring, the obstacles in the roadway should be cleared, so that the roadway in the whole measurement range can meet the measurement requirements.

(2) Because of the symmetry of the upper and lower, left and right sides of the rectangular roadway, 1/4 of the cross section of the rectangular roadway is selected for measurement. The specific values of the distance between measuring surfaces l, the number of measuring surfaces N, the height of measuring lines h, the length of measuring lines L and the number of anemometers n of each measuring line are determined according to the cross-section size of the roadway. Then the anemometer installation rod is assembled according to the measuring line length L, the measuring surface number N and the number of anemometers per line n. The specific anemometer layout diagram is shown in Figure 19.

(3) In this experiment, four kinds of cross-section sizes and corresponding airflow velocity conditions are selected, which are: section size 4.8 × 3.4 m with mean airflow velocity of 0.65 m/s; section size 5.0 × 3.0 m with mean airflow velocity of 2.6 m/s; section size 4.8 × 3.4 m with mean airflow velocity of 2.8 m/s, and section size 4.5 × 2.8 m with mean airflow velocity 4.8 m/s.

(4) All the data acquisition instruments are turned on and placed in the position of the lower tuyere of the measured roadway, and the ventilation parameter collector installed on the data acquisition instrument automatically and uninterruptedly collects the airflow velocity values displayed on the electronic airflow velocity measuring instrument. After the data becomes stable, another data acquisition instrument is used to take pictures and record the data. The specific layout diagram is shown in Figure 20.

4.3.3 Analysis of field experimental data

Four groups of experiments are conducted by using the above experimental methods, and the measured data are fitted into a curve according to the boundary conditions with Sufer software, and the boundary points are taken every 50 mm. The results are shown in Figure 21. It can be seen that the airflow velocity isoline in the roadway section is approximately rectangular. Similarly, the closer to the roadway wall, the denser the airflow velocity isoline, indicating that the airflow velocity gradient near the wall is larger; and the closer to the central part of the roadway, the sparser the airflow velocity isoline is, indicating that the smaller the airflow velocity gradient is, the less the airflow velocity variation is. In the same roadway, the larger the inlet airflow velocity is, the smaller the thickness of the near-wall velocity variation layer is, that is, the thickness of the boundary layer decreases with the increase of airflow velocity. The red line in the figure is the measured mean airflow velocity line. Under the above four experimental conditions, the average distance from the measured mean airflow velocity line to the roadway roof is 0.3946, 0.3952, 0.3437, and 0.3176 m, respectively.

To verify the theoretical model, the average distance value $d_3$ from the measured position of the mean airflow velocity line to the roof and the distance $d_4$ from the position of the theoretical mean airflow velocity line to the roof are compared, as shown in Table 12. It can be seen that the position errors of the average airflow velocity line measured in the four rectangular roadway sections selected by Sima Coal Mine and calculated by the theoretical model are all less than 5%, and the theoretical model is reliable.
FIGURE 19  Schematic layout of anemometer in a rectangular roadway. (A) The position of measuring line and cross section and (B) the installation position of anemometers.

FIGURE 20  The layout of the data acquisition instruments in test roadway
CONCLUSIONS

In this study, the distribution law of airflow velocity in typical roadway sections (namely rectangle and semi-circular arch sections) have been studied by theoretical analysis, numerical simulation and field tests. The main conclusions are as follows:

(1) Based on Boussinesq theory and Pelant turbulence theory, the calculation model of position of mean airflow velocity line in rectangular and semicircular arch roadway is established, which is \( y = \alpha \ln a^{1.5} \). The calculation model shows that the position of mean airflow velocity line is only related to roadway section size and has nothing to do with other factors.

(2) A numerical simulation was conducted to study the airflow velocity distribution in rectangular and semicircular arch roadways. The contour line of airflow velocity in the roadway section is consistent with the shape of the roadway section, and the isoline of airflow velocity is basically parallel to the roadway wall. Besides, the closer to the roadway wall, the denser the airflow velocity isoline, indicating that the airflow velocity gradient near the wall is larger. And the thickness of the boundary layer

FIGURE 21  Airflow velocity distribution in rectangular roadway under different conditions. (A) 4.8 × 3.4 m, 0.65 m/s; (B) 4.8 × 3.4 m, 2.6 m/s; (C) 5.0 × 3.0 m, 2.8 m/s; and (D) 4.5 × 2.8 m, 4.8 m/s.

TABLE 12  Comparison of the field test results in Sima Coal Mine and theoretical results of the distance from the mean airflow velocity line to the roof

| Section type  | Section size (m×m) | Airflow velocity (m/s) | Field measuring value \(d_3\) (m) | Theoretical value \(d_4\) (m) | Error \((\frac{|d_3 - d_4|}{d_4} \times 100\%)\) |
|---------------|-------------------|------------------------|-------------------------|------------------------|-------------------|
| Rectangular   | 4.8 × 3.4         | 0.56                   | 0.3946                  | 0.3793                  | 4.0%              |
|               | 4.8 × 3.4         | 2.6                    | 0.3952                  | 0.3793                  | 4.2%              |
|               | 5.0 × 3.0         | 2.8                    | 0.3437                  | 0.3347                  | 2.7%              |
|               | 4.5 × 2.8         | 4.8                    | 0.3176                  | 0.3124                  | 1.7%              |

5 | CONCLUSIONS

In this study, the distribution law of airflow velocity in typical roadway sections (namely rectangle and semicircular arch sections) have been studied by theoretical analysis, numerical simulation and field tests. The main conclusions are as follows:
decreases with the increase of airflow inlet velocity. The numerical simulation results also verify the correctness of the calculation model of position of mean airflow velocity line in rectangular and semicircular arch roadways.

To further verify the correctness of the calculation model and numerical simulation results, field tests have been conducted in Chongqing Research Institute and Sima Coal Mine. The measured distribution law of airflow velocity is consistent with the numerical simulation. And the calculation model of position of mean airflow velocity line in rectangular and semicircular arch roadways was further verified by field test. And errors are all less than 5%, which indicates the theoretical model is reliable.

AUTHOR CONTRIBUTIONS
Qinghua Zhang conceived and wrote the paper; Guang Luo provided the ideas and designed the experiments. Shuqi Zou performed the experiments and collected the data.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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REFERENCES
1. Li XL, Cao ZY, Xu YL. Characteristics and trends of coal mine safety development. Energy Sources A Recov Util Environ Effects. 2020. doi:10.1080/15567036.2020.1852339
2. Li XL, Chen SJ, Wang S, Zhao M, Liu HH. Study on in situ stress distribution law of the deep mine: taking linyi mining area as an example. Adv Mater Sci Eng. 2021;2021:1-11. doi:10.1155/2021/5594181
3. Liu HY, Zhang BY, Li XL, et al. Research on roof damage mechanism and control technology of gob-side entry retaining under close distance gob. Eng Fail Anal. 2022;138:106331.
4. Liu SM, Li XL, Wang DK, Zhang DM. Investigations on the mechanism of the microstructural evolution of different coal ranks under liquid nitrogen cold soaking. Energy Sources A Recov Util Environ Effects. 2020.
5. Li XL, Chen SJ, Zhang QM, Gao X, Feng F. Research on theory, simulation and measurement of stress behavior under regenerated roof condition. Geomech Eng. 2021;26(1):49-61.
6. Li XL, Chen SJ, Liu SM, Li ZH. AE waveform characteristics of rock mass under uniaxial loading based on Hilbert-Huang transform. J Cent South Univ. 2021;28(6):1843-1856.
7. Jia J, Jia P, Li Z. Theoretical study on stability of mine ventilation network based on sensitivity analysis. Energy Sci Eng. 2020;8:2823-2830.
8. Tuta M, Brodny J, Szurgacz D, Sobik L, Zhironkin S. The impact of the ventilation system on the methane release hazard and spontaneous combustion of coal in the area of exploitation—a case study. Energies. 2020;13(18):4891.
9. Yu J, Li Z, Wang W. Influence of gas outburst dynamic flow on mine ventilation system. AIP Adv. 2021;11(7):075223.
10. Sun B, Cheng WM, Wang JY, Wu G, Zhang M. On the conversion mechanism and control technology of gob under close distance gob. J Saf Sci Technol. 2021;28:2067-2078.
11. Jia J, Jia P, Li Z. Measurement and simulation of flow in a long heading face. J China Coal Soc. 2021;36(4):892-898.
12. Liu J, Song Y, Liu M, Liu Y, Deng L. Experimental study on distributions of airflow in four rectangular section roadways with different supporting methods in underground coal mines. Tunn Undergr Space Technol. 2015;46:85-93.
13. Luo Y, Zhao Y, Wang Y, Chi M, Tang H, Wang S. Distribution of airflow in mine tunnel. J Cent South Univ. 2021;28:2067-2078.
14. Liu J, Song Y, Liu M, Liu Y, Deng L. Experimental study on distributions of airflow in straight roadway section based on LDA. J Saf Sci Technol. 2015;11(12):65-72.
15. Liu J, Song Y, Li X, Bai C, Deng L, Wu G. Experimental study on airflow velocity distribution of the straight roadway and sudden enlarged sections based on LDA. J China Coal Soc. 2016;41(4):892-898.
16. Song Y, Liu J, Li X, Liu Y, Tian R, Zhao C. Experiment and numerical simulation of average wind speed distribution law of airflow in mine tunnel. China Saf Sci J. 2016;26(6):146-151.
17. Li B, Liu J, Song Y, Wu G, Zhang M. On the conversion between the mean airflow velocity and that of the individual.
22. Zhang S. Study on measurement and change law of airflow velocity in cross section of coal mine ventilation roadway. *Min Saf Environ Protect*. 2019;46(4):17-20.

23. Li Y, Li Y, Wu J, Yao Y. Experimental study on air flow distribution law of the roadway. *Nonferrous Metals Min Sect*. 2019;71(5):102-110.

24. Wei LJ, Wang MW, Li S, Wei ZK. Line airflow velocity distribution model of rectangular tunnel cross-section. *Therm Sci*. 2019;23(3):1513-1519.

25. Ligeza P, Poleszczyk E, Skotniczny P. A Three-dimensional modelling of the structure of flow parameter fields in mine drifts. *Arch Min Sci*. 2009;54(5):601-621.

26. Pezzotti S, D’Iorio J, Nadal-Mora V, Pesarini A. A wind tunnel for anemometer calibration in the range of 0.2-1.25 m/s. *Flow Meas Instrum*. 2011;22(4):338-342.

27. Luo Y, Zhao Y. Field and experimental research on airflow velocity boundary layer in cao mine roadway. *Arch Min Sci*. 2020;65(2):255-270.

28. Zhou L, Yuan L, Thomas R, Iannacchione A. Determination of velocity correction factors for real-time air velocity monitoring in underground mines. *Int J Coal Sci Technol*. 2017;4(4):322-332.

29. Ren YX, Chen HX. *Fundamentals of Computational Fluid Dynamics*. Tsinghua University Press; 2006.

30. Wang DM. *Mine Ventilation and Safety*. China University of Mining and Technology Press; 2012.

31. Zhang ZX, Dong ZN. *Viscous Fluid Mechanics*. Tsinghua University Press; 2011.

32. Li XB, Liu J, Qin HY, Wang HD, Hu Y. Method for air velocity measurement with single-point under the influence of turbulent fluctuation. *J North China Inst Sci Technol*. 2018;15(2):1-9.

33. Wang YQ, Xin YX, Wu YK, Wang JB. Influence of tunnel section shape on friction loss. *J Xi'an Technol Univ*. 2015;35(8):617-622.

34. Wang HF. Simulation study on monitoring and measuring location of average air velocity in section of mine roadway based on fluent. *Coal Sci Technol*. 2015;43(8):92-96.

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