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Research on the Distribution Law of Wind Speed on the Cross-section of Tunnels in Wuhushan Coal Mine

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Abstract

In response to the problem that the accuracy of wind speed monitoring in the tunnels of Wuhushan Coal Mine is difficult to meet decision-making needs, the distribution law of wind speed in the cross-section of rectangular and semi-circular arched tunnels was taken as the research object. Using a combination of theoretical analysis and numerical simulation, the distribution law of wind speed in the cross-section of Wuhushan Coal Mine tunnels under different conditions was systematically studied. The research results indicate that the position of the average wind speed line in the roadway is only related to the size of the roadway and is independent of other main control factors. The distance between the average wind speed line and the two sides (top and bottom) of the roadway is about 0.11 times the width (height) of the roadway. Numerical simulation shows the distribution pattern of wind speed in different types of tunnel sections under different conditions, and the ratio of maximum wind speed to average wind speed in tunnel sections is about 1.2. The distance between the average wind speed line of a semi-circular arch roadway and the roof is 10.76% to 1.12% of the roadway height, while the distance between the average wind speed line of a rectangular roadway and the roof is 10.76% to 11.03% of the roadway height, with an error of less than 4% compared to the theoretical calculation results.

Keywords

Mine Ventilation; Tunnel Cross-section; Tunnel Wind Speed; Distribution Pattern; Numerical Simulation.

1. Introduction

The intelligentization of coal mines is a necessary path for the transformation and development of the coal industry. As coal mining enters a new era of safety and intelligence, the deep integration of intelligent technology and the coal industry will inevitably lead to revolutionary changes in coal production methods, promoting a huge improvement in coal mine production efficiency and safety level [1]. The intelligent technology of mine ventilation can monitor changes in underground ventilation parameters in real time, ensuring timely and on-demand air supply at various periods and locations, and is an indispensable and important component of mine intelligent construction [2,3]. At present, the monitoring of wind speed and air volume in the tunnels of Wuhushan Coal Mine mainly relies on manual wind measurement and sensor monitoring. The use of traditional ventilation parameter monitoring equipment cannot meet the requirements of rapid and accurate intelligent ventilation parameter measurement, which misleads ventilation technology management and decision-making. Therefore, in response to the problem that the accuracy of wind speed monitoring in the tunnels of Wuhushan Coal Mine is difficult to meet decision-making needs, it is particularly important to study the distribution law of wind speed in the cross-section of coal mine tunnels.

In recent years, many domestic scholars have done a lot of work on the distribution law of wind speed in tunnel sections [4,5]. Wang Heng et al. [6] studied the distribution law of wind speed in coal mine tunnels under different factors, and the results showed that roughness, tunnel aspect ratio, section position, and inlet wind speed did not have any effect on the contour of wind speed distribution in tunnels. Hu Jianhua et al. [7] constructed three core arch tunnel models under different conditions and studied the effects of tunnel height, roof roughness, and inlet wind speed on tunnel wind speed distribution. The results showed that surface roughness had a significant impact on tunnel ventilation and cross-sectional wind speed distribution. Sun Liang et al. [8] established a mathematical model for mine ventilation and verified the reliability of the model through numerical simulation. Liu Jian et al. [9,10] used a laser Doppler velocimeter to experimentally test the velocity of the cross-section of a straight tunnel and a sudden expansion tunnel. The results showed that the magnitude and direction of the wind speed followed a normal Gaussian distribution. Ding Cui et al. [11] used numerical simulation to study the distribution law of wind speed on the cross-section of tunnels and proposed the concept of "key loop". Yang Yu [12] and Zhang Shiling [13] used theoretical analysis to conclude that the distribution of wind speed in tunnels conforms to the law of turbulent velocity variation, and provided their logarithmic distribution formula. Lu Guangli et al. [14] studied the variation law of airflow in tunnels at different turning angles, constructed 12 models using numerical simulation software, and conducted simulation experiments under different wind speeds. The results showed that the variation law of airflow in tunnels remained consistent under different wind speeds, and the position of the average wind speed point in the tunnel remained fixed. Wang Hanfeng et al. [15] used numerical simulation software to simulate the airflow field of the tunnel model under different conditions, and obtained the relationship between the average wind speed line position and the tunnel cross-section.

In summary, Chinese scholars have paid less attention to the influence of the position of the average wind speed line in the study of the distribution law of wind speed in coal mine tunnels, and the research method is too single, failing to fully consider the comprehensive application of multiple experimental methods, and verifying the reliability of theoretical calculation models from multiple aspects. Therefore, the author adopts a combination of theoretical calculation and numerical simulation to determine the main controlling factors affecting the distribution of wind speed in tunnels, establishes a mathematical model of the relationship between the average wind speed line of different tunnel section types and the distance between the two sides or top and bottom of the tunnel, and reveals the distribution law of wind speed under different conditions of tunnel section.

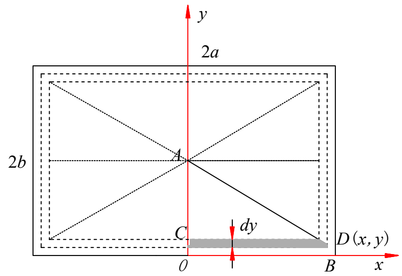
2. Theoretical Model for the Position of the Average Wind Speed Line

2.1 Analysis of the Influence of Wind Speed Patterns in Tunnels

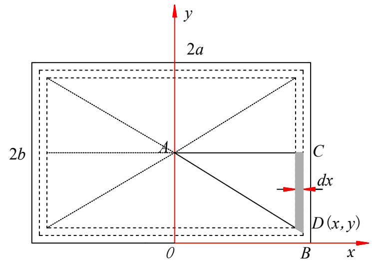
A calculation model for the distribution law of wind speed in rectangular tunnels is constructed based on the Boussinesk theory and Prandtl turbulence theory [16], as shown in Figure 1. The two closed dashed lines in the figure represent the wind speed contour lines at a distance dy, which are parallel to the tunnel wall. The wind speed corresponding to any point in the figure is:

$$\mu = \sqrt{\frac{\alpha \bar{v}^2}{\rho}} \frac{1}{k} \ln y + C \tag{1}$$

In the formula: μ is wind speed at any point, m/s; $\bar{v}$ is average wind speed of tunnel section, m/s; ρ is air density in the tunnel, kg/m3; y is the distance from any flow layer in the tunnel to the tunnel wall, m; α is the coefficient of frictional resistance; k is mixed length coefficient; C is an integral constant.



(a) to the top and bottom of the tunnel



(b) to the left and right sides of the tunnel

Figure 1. Calculation model for the average wind speed line position in rectangular tunnels

In a rectangular tunnel, the airflow corresponding to the AOB area Q_1 is:

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

In the formula: a is half of the length of the rectangular roadway; b is half the width of a rectangular roadway.

According to the symmetry of the rectangular tunnel, the airflow of the entire cross-section of the rectangular tunnel Q is:

$$Q = 8Q_1 = 4afb \ln b - 6afb + 4abC \tag{3}$$

From the relationship between air volume and cross-sectional area of the tunnel, it can be concluded that the average wind speed of the rectangular section in Figure 1 (a) is:

$$\bar{v} = \frac{Q}{4ab} \tag{4}$$

Assuming that the wind speed at any point in the tunnel is the average wind speed of the tunnel, the distance from the average wind speed line of the rectangular tunnel section to the top and bottom plate after simplification is:

$$y = e^{\ln b - 1.5} \tag{5}$$

Similarly to Figure 1 (a), the distance from the average wind speed line of the cross-section of the roadway to the left and right sides of the roadway can be obtained as:

$$x = e^{\ln a - 1.5} \tag{6}$$

Formulas (5) and (6) represent the relationship between the average wind speed line and the tunnel wall. From the expression, it can be seen that the position of the average wind speed line in a rectangular tunnel is only related to the tunnel size and is independent of other main control factors. Similarly, through theoretical derivation of the average wind speed line for rectangular tunnels with semi-circular arches, trapezoids, and circular cross-sections, consistent conclusions have been drawn.

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Therefore, the position of the average wind speed line in the roadway is only related to the size of the roadway and is not related to other controlling factors.

2.2 Theoretical Calculation of Average Wind Speed Line Position

In order to further discuss the influence of tunnel size on the position of the average wind speed line, common types of tunnel sizes in rectangular tunnels are listed, and the corresponding average wind speed line positions for different tunnel sizes are calculated. The influence of tunnel height and width on the position of the average wind speed line is discussed. According to the model formula, the results obtained are shown in Tables 1 and 2. According to Tables 1 and 2, it can be seen that the distance between the average wind speed line and the top and bottom (left and right sides) of the tunnel is positively correlated with the height (width) of the tunnel. The distance between the average wind speed line and the two sides (top and bottom) of the tunnel is about 0.11 times the width (height) of the tunnel.

Table 1. Average wind speed line positions corresponding to different tunnel heights

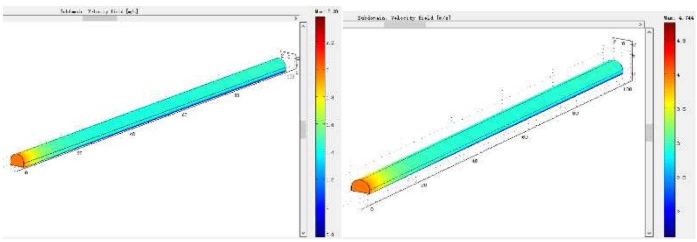
Tunnel height (m)	2.5	3.0	3.5	4.0	4.5	5.0
Distance from top and bottom plate (m)	0.2789	0.3347	0.3905	0.4462	0.5020	0.5578
Distance from roof/height of roadway	0.11156	0.11157	0.11157	0.11155	0.11156	0.11156

Table 2. Average wind speed line positions corresponding to different tunnel widths

Tunnel width (m)	3.0	3.5	4.0	4.5	5.0	5.5
Distance from left and right sides (m)	0.3347	0.3905	0.4462	0.5020	0.5578	0.6136
Distance from left and right sides/roadway width	0.11157	0.11157	0.11155	0.11156	0.11156	0.11156

3. Numerical Simulation of the Distribution Law of Wind Speed on the Cross-section of Two Tunnels

Based on the actual conditions of Wuhushan Coal Mine, 2 rectangular tunnel sizes and 2 semi-circular arch tunnel sizes, 4 sets of inlet wind speeds, and 2 support types corresponding to tunnel types were selected for simulation calculations. A total of 4 models and 16 sets of simulation experiments were conducted. Establish geometric models for different cross-sectional sizes of semi-circular arches and rectangular tunnels, and provide basic simulation parameters for the two types of tunnels under different wind speeds and support methods. The length of the tunnel models is 100 meters. When modeling, the length, height, and width of the selected roadway model are in the X, Y, and Z directions. The numerical simulation geometric model is shown in Figures 2 to 3. The COMSOL Multiphysics software is used to simulate the cross-sectional wind speed of semi-circular arches and rectangular tunnels under different cross-sectional sizes, inlet wind speeds (0.8m/s, 2m/s, 4m/s, 6m/s), and different support forms (anchor spraying and anchor net). A total of 16 simulation schemes are used.



(a) 4m×3m (b) 4.5m×3.3m

Figure 2. Semi-circular arch roadway model

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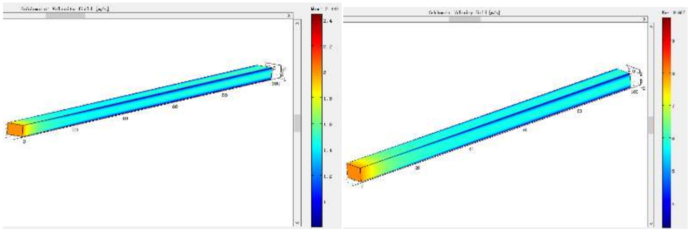


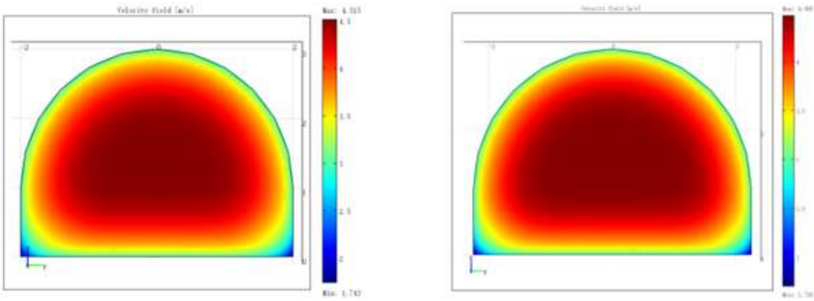
(a) 4m×3m (b) 5m×3.5m

Figure 3. Rectangular tunnel model

4. Simulation Results

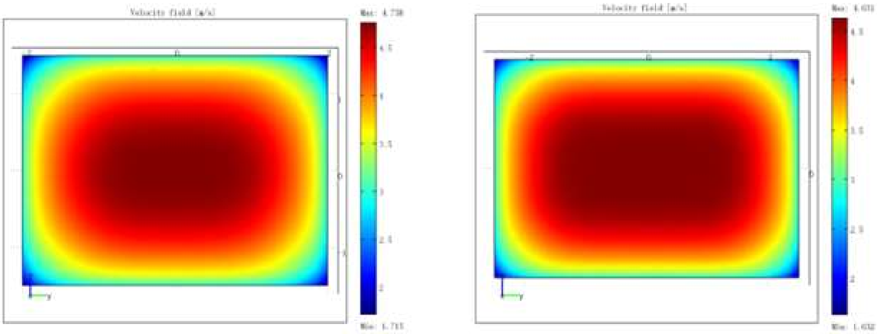
4.1 Distribution Characteristics of Wind Flow Field on Tunnel Cross-section

Contour maps with wind speeds of 4.0m/s is selected, as shown in Figures 4~5. In establishing a simplified velocity model, considering avoiding the influence of eddy currents in the tunnel flow field, a cross-sectional data at a distance of 50m from the tunnel entrance is selected as the basis. At this time, the airflow velocity field on the cross-section remains basically unchanged and reaches a fully developed state. From Figures 4 to 5, it can be seen that the contour line of the wind speed contour line on the tunnel section is consistent with the shape of the section, and the wind speed contour line is basically parallel to the tunnel wall. The wind speed contour line expands from the central part of the tunnel section to the tunnel wall. The closer the wind speed contour line is to the wall of the tunnel, the denser it is, indicating that the wind speed gradient is larger near the wall, and the sparser the wind speed contour line is closer to the middle of the tunnel, indicating that the wind speed gradient is smaller and the central wind speed of the tunnel is basically equal. In the same tunnel, the higher the average wind speed, the smaller the thickness of the near wall velocity variation layer, that is, the thickness of the boundary layer decreases with the increase of wind speed.



(a) 4m×3m (b) 4.5m×3.3m

Figure 4. Contour map of velocity distribution on different cross-sections of a semi-circular arch roadway



(a) 4m×3m (b) 4.5m×3.3m

Figure 5. Contour map of velocity distribution at different inlet wind speeds in a rectangular tunnel

4.2 Distribution Pattern of Wind Speed on the Central Axis

Based on the distribution of cross-sectional wind speed at X=50m in the tunnel, the inlet wind speeds are taken as 0.8m/s, 2m/s, 4m/s, and 6m/s, respectively. According to the selected tunnel type in the simulated scheme, an empirical formula for calculating the average wind speed of the tunnel section is obtained through the wind speed at the tunnel section point, and the relationship with the average wind speed of the tunnel is found. Using Origin 8.0 again to fit the non-linear functions of point velocity and average wind speed, the results are shown in Table 3.

Table 3. Fitting results of wind speed distribution on the central axis

Programme	Distance from the central axis to the top plate d/m	Inlet velocity 0.8m/s	Inlet velocity 2m/s	Inlet velocity 4m/s	Inlet velocity 6m/s
4m × 3m rectangular roadway	$d \subseteq (0,1.25]$	$v_{0.8}/\bar{v}=1.1839+0.1633\ln d$	$v_2/\bar{v}=1.1573+0.1391\ln d$	$v_4/\bar{v}=1.1406+0.1267\ln d$	$v_6/\bar{v}=1.1332+0.1189\ln d$
	$d \subseteq [1.25,1.5]$	$v_{0.8}/\bar{v}=1.225$	$v_2/\bar{v}=1.21$	$v_4/\bar{v}=1.185$	$v_6/\bar{v}=1.175$
5m×3.5m rectangular roadway	$d \subseteq [0,1.5]$	$v_{0.8}/\bar{v}=1.1605+0.1686\ln d$	$v_2/\bar{v}=1.1179+0.1221\ln d$	$v_4/\bar{v}=1.1065+0.1113\ln d$	$v_6/\bar{v}=1.0999+0.105\ln d$
	$d \subseteq [1.5,1.75]$	$v_{0.8}/\bar{v}=1.225$	$v_2/\bar{v}=1.175$	$v_4/\bar{v}=1.1575$	$v_6/\bar{v}=1.147$
4m × 3m semi-circular arch roadway	$d \subseteq [0,1.25]$	$v_{0.8}/\bar{v}=1.173+0.153\ln d$	$v_2/\bar{v}=1.1157+0.1075\ln d$	$v_4/\bar{v}=1.1055+0.0975\ln d$	$v_6/\bar{v}=1.0985+0.092\ln d$
	$d \subseteq [1.25,1.5]$	$v_{0.8}/\bar{v}=1.2125$	$v_2/\bar{v}=1.145$	$v_4/\bar{v}=1.1275$	$v_6/\bar{v}=1.118$
4.5m×3.3m semi-circular arch roadway	$d \subseteq [0,1.6]$	$v_{0.8}/\bar{v}=1.1476+0.1473\ln d$	$v_2/\bar{v}=1.102+0.1038\ln d$	$v_4/\bar{v}=1.0894+0.0908\ln d$	$v_6/\bar{v}=1.0827+0.084\ln d$
	$d \subseteq [1.6,1.65]$	$v_{0.8}/\bar{v}=1.2$	$v_2/\bar{v}=1.135$	$v_4/\bar{v}=1.1175$	$v_6/\bar{v}=1.107$

4.3 Comparison of Numerical Simulation and Theoretical Model Results

There are seven indicators to analyze the relationship between wind speed and average wind speed: average wind speed, tunnel width, tunnel height, ratio of maximum wind speed to average wind speed, distance d from numerical simulation average wind speed line to roof, distance D from theoretical calculation average wind speed line to roof, and error between numerical simulation results and theoretical calculation results. Verify the reliability of the theoretical calculation model through comparative analysis. The comparison results are shown in the Table 4.

According to Table 4, the ratio of the maximum wind speed to the average wind speed at the tunnel section is approximately 1.2. The distance between the average wind speed line of a semi-circular arch roadway and the roof is 10.76% to 1.12% of the roadway height, while the distance between the average wind speed line of a rectangular roadway and the roof is 10.76% to 11.03% of the roadway height. The error between the theoretical calculation results and the numerical simulation results is within 4%, and the conclusions of the two research methods are consistent, verifying the reliability of the theoretical model.

Table 4. Comparison between theoretical models and numerical simulation results

Tunnel type	Section size(Wide × Height, m)	Average wind speed(m/s)	Maximum wind speed/ Average wind speed	Simulated average wind speed line to roof distance d (m)	Theoretical average wind speed line to roof distance D (m)	Error($\left\|\frac{d-D}{D}\right\| \times 100\%$)
Semi circular arch roadway	4 ×3	0.8	1.2125	0.3228	0.3347	3.56%
		2.0	1.1450	0.3286	0.3347	1.84%
		4.0	1.1275	0.3305	0.3347	1.25%
		6.0	1.1180	0.3266	0.3347	2.42%
	4.5 ×3.3	0.8	1.2000	0.3671	0.3682	0.29%
		2.0	1.1350	0.3621	0.3682	1.66%
		4.0	1.1175	0.3628	0.3682	1.47%
		6.0	1.1070	0.3628	0.3682	1.47%
Rectangular tunnel	4 ×3	0.8	1.2250	0.3243	0.3347	3.11%
		2.0	1.2100	0.3228	0.3347	3.57%
		4.0	1.1850	0.3297	0.3347	1.51%
		6.0	1.1750	0.3262	0.3347	2.54%
	4.5 ×3.3	0.8	1.2250	0.3860	0.3905	1.16%
		2.0	1.1750	0.3808	0.3905	2.50%
		4.0	1.1575	0.3841	0.3905	1.64%
		6.0	1.1470	0.3862	0.3905	1.10%

5. Conclusion

In response to the problem that the accuracy of wind speed monitoring in the tunnels of Wuhushan Coal Mine is difficult to meet decision-making needs, a combination of theoretical analysis and numerical simulation methods is used to study the relationship between the position of the average wind speed line and the distance from the tunnel wall. The distribution law of wind speed on the cross-section of rectangular and semi-circular arch tunnels is simulated and summarized. The main conclusions are as follows:

(1) A calculation model for the average wind speed line position of rectangular and semi-circular arch tunnels is established. After calculation, the expressions for the average wind speed line position of two typical tunnel sections were obtained as follows: $y \approx 0.11a$. The calculation result shows that the average wind speed line position of the tunnel is only related to the tunnel size and is independent of other main control factors. The distance between the average wind speed line and the two sides (top and bottom) of the tunnel is about 0.11 times the width (height) of the tunnel.

(2) The wind speed contour line is basically parallel to the tunnel wall. The wind speed gradient near the tunnel wall is large, while the wind speed gradient in the middle of the tunnel is small. The thickness of the boundary layer decreases with increasing wind speed.

(3) The ratio of the maximum wind speed to the average wind speed of the tunnel section is about 1.2. The distance between the average wind speed line of a semi-circular arch roadway and the roof is 10.76% to 1.12% of the roadway height, while the distance between the average wind speed line

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of a rectangular roadway and the roof is 10.76% to 11.03% of the roadway height. The simulation results have an error of less than 4% compared to the theoretical calculation results.

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