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Experimental Study on the Distribution Law of Wind Speed in Rectangular Section Tunnels of Coal Mines

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Abstract

Ventilation is the cornerstone of coal mine safety production, and accurate monitoring of ventilation parameters is the fundamental guarantee for ventilation technology decision-making. A calculation model for the average wind speed line position in rectangular section tunnels of coal mines was established based on the Boussinesk theory and Prandtl turbulence theory to address the issue of difficulty in meeting decision-making needs in wind speed monitoring accuracy. The airflow field of rectangular section tunnels under different wind speed conditions was measured at the coal mine site, and the average position of the measured average wind speed line was obtained. The comparison and verification with the theoretical calculation results were carried out, with an absolute error of less than 5%.

Keywords

Mine Ventilation; Rectangular Cross-section Roadway; Wind Speed Distribution; Average Wind Speed.

1. Introduction

The dominant position of coal in China's energy consumption will not change, with China's raw coal production reaching 4.71 billion tons in 2023. Due to the complexity of the geological structure of coal fields in China, coal mining often accompanies disasters such as gas explosions, coal dust explosions, mine water inrush, and rockburst [1]. These disasters not only cause casualties and property damage, but also have a serious impact on the normal production of coal mines. The ventilation system of coal mines is one of the important means to ensure the safety of coal mine production. The ventilation system can effectively reduce the gas concentration in the mine, eliminate harmful gases and dust, and ensure the safety and health of miners [2-3].

In the context of coal geological structure and disasters, the importance of coal mine ventilation system has become more prominent. On the one hand, the complex geological structure makes the distribution of harmful gases such as gas more uneven. The ventilation system needs to control the direction and volume of air flow more accurately to ensure the effective elimination of harmful gases. On the other hand, the frequent occurrence of disasters also requires ventilation systems to have higher reliability and stability, which can play a role in critical moments and prevent the expansion and deterioration of disasters. In recent years, scholars at home and abroad have conducted research on the distribution law of wind speed in tunnel cross-sections, and have achieved rich results. Zhang Shiling [4-5] constructed a logarithmic distribution formula for wind speed field under the turbulent form of tunnel airflow. Qiao Anliang [6] measured the wind speed at the cross-section of the roadway under three different support forms: anchor mesh and cable support, anchor spray support, and flat wall support,

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and studied the distribution law of wind speed at the cross-section of the roadway under different support methods. Yu Fangchao et al. [7] conducted air volume parameter measurements on the rectangular, trapezoidal, and triple arch tunnels of the 630 track roadway and intake sub roadway in Wangzhuang Mine. Based on the measured parameters, Fluent was used to conduct numerical simulation research on the cross-sectional wind speed of the tunnels. Wang Heng et al. [8] simulated the cross-sectional position, inlet wind speed, aspect ratio, and roughness of tunnels under different conditions, and quantitatively analyzed and determined the distribution pattern of tunnel wind speed under different conditions. Sun Liang et al. [9] studied the distribution law of wind speed in large cross-section tunnels and the principle of wind speed testing. They used the "multi-point grid wind measurement method" and traditional manual testing methods for on-site measurement, and compared the simulation results with the on-site measurement results using FLUENT software to verify the rationality of selecting a stable zone for average wind speed distribution. Therefore, based on on-site measurements, the author further explores the wind speed distribution law of rectangular section tunnels in coal mines, providing a certain reference for improving the accuracy of obtaining ventilation parameters such as wind speed and air volume.

2. Theoretical Distribution of Wind Speed in a Rectangular Cross-section Roadway

Based on the symmetrical distribution characteristics of wind speed within the cross-section of a rectangular tunnel, a mathematical formula for calculating the wind speed of the cross-section of the tunnel is obtained, and the relationship function between the position of the average wind speed line and the position of the tunnel wall is then solved, as shown in Figure 1.

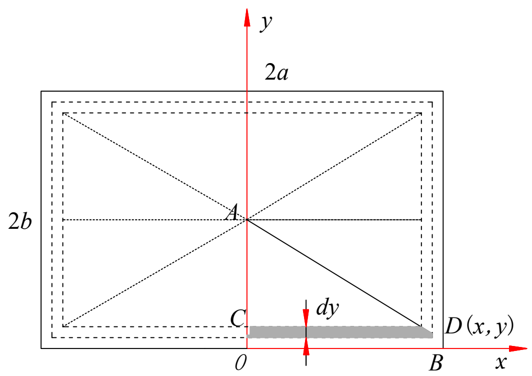

Figure 1. Calculation model for the average wind speed line position in rectangular tunnels

Based on the Boussinesk theory and Prandtl turbulence theory, the integral expression for the air volume corresponding to the AOB area in a rectangular tunnel is:

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

Where, μ - wind speed at any point, m/s; $\bar{v}$ - Average wind speed of tunnel section, m/s; ρ - Air density inside the tunnel, kg/m3; y - distance from any flow layer in the tunnel to the tunnel wall, m; α - Is the coefficient of frictional resistance; k - Mixed length coefficient; C - is the integral constant.

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According to the symmetry of the rectangular tunnel, the overall air volume is 8 times the corresponding air volume of AOB, order $f=\frac{1}{k}\sqrt{\frac{\alpha\bar{v}^2}{\rho}}$, so the expression for the air volume of the rectangular section Q is:

$$Q=8\int_{0+}^{b}(f\ln y+C)\left(a-\frac{a}{b}y\right)dy=4afb\ln b-6afb+4abC \tag{2}$$

From the relationship between air volume and cross-sectional area of the tunnel, the expression for the average wind speed of the rectangular section can be obtained:

$$\bar{v}=\frac{Q}{4ab}=f\ln b-1.5f+C \tag{3}$$

The calculation expression for the distance from the average wind speed line of the rectangular tunnel section to the top and bottom plate is:

$$\mathrm{y}=e^{\ln b-1.5} \tag{4}$$

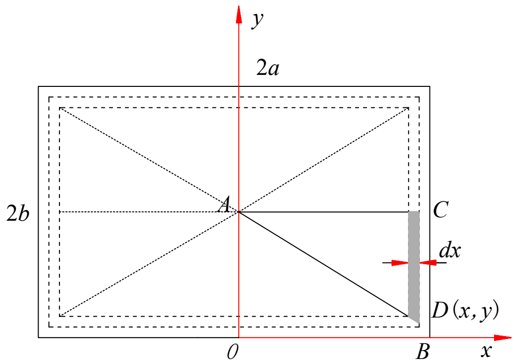

Figure 2. Calculation model for wind speed distribution in rectangular tunnels

Establish an integral expression for the air volume along the x-axis for the rectangular tunnel in Figure 2, and the expression for the air volume corresponding to ABC Q_2 is:

$$Q_2=\int_0^a\left(\sqrt{\frac{\alpha\bar{v}^2}{\rho}}\frac{1}{k}\ln x+C\right)\left(b-\frac{b}{a}x\right)dx \tag{5}$$

The expression for the airflow of a rectangular cross-section Q is:

$$Q=8\int_{0+}^{a}(f\ln x+C)\left(b-\frac{b}{a}x\right)dx=4afb\ln a-6afb+4abC \tag{6}$$

From the relationship between air volume and cross-sectional area of the tunnel, the expression for the average wind speed of the rectangular section in Figure 2 can be obtained as follows:

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$$\overline{v} = \frac{Q}{4ab} = f \ln b - 1.5 f + C \tag{7}$$

The formula for calculating the distance from the average wind speed line of the rectangular tunnel section to the left and right sides of the tunnel is:

$$x = e^{\ln a - 1.5} \tag{8}$$

3. Experimental Locations and Methods

Select some tunnels under the Sima Mine of Lu'an Group as the on-site experimental tunnels, with a rectangular shape. Four types of rectangular tunnels with wind speeds (0.65, 2.6, 2.8, 4.8 m/s) were selected for measurement. This experiment used 16 CFD15 coal mine electronic anemometers and 16 YHC mine intrinsic safety data acquisition instruments. At present, the ventilation system of Sima Mine adopts a partitioned ventilation system, which includes the main and auxiliary shafts, as well as the new inlet shaft for air intake, and the central return shaft and the new return shaft for air return. The total inlet air volume of the mine is 19578m3/min, and the total return air volume is 19200m3/min. The two return shaft ventilators are both mechanical extraction and axial flow fans. The central return shaft fan model is FBCDZ-10-NO.29, with a motor power of 2×630kW and a negative pressure of 2520Pa. The model of the new return air shaft fan is FBCDZNo38, with a negative pressure of 1770Pa, one in use and one as backup. The central return air vertical shaft fan bears the task of supplying air to the first and second mining areas of the mine, and the new return air vertical shaft fan is responsible for the air supply task in the third mining area of the mine. At present, both the underground mining area and the mining face are independently ventilated. The first mining area is equipped with "two inlets and two returns", which includes the intake of the track roadway and the belt roadway, the dedicated return airway, and the auxiliary return airway. The second mining area is equipped with "three inlets and one return", and the third mining area is equipped with "three inlets and one return". In 2020, the ventilation capacity of the mine was approved to be 3.3 million t/a, which meets the actual production needs.

Due to the accumulation of various equipment or other obstacles in coal mines, the airflow state is difficult to stabilize, and it is very difficult to measure the wind speed in the same section at the same time. Therefore, it was chosen that the tunnel within 100m had almost no deformation, was relatively regular and had less accumulation, and the mirror step method was used to arrange the wind meter for measurement. The shape of the experimental section and the wind speed conditions inside the section were self selected underground. In this experiment, four different section sizes and corresponding wind speed conditions were selected under the Sima mine, namely: rectangular 4.8m × 3.4m, with an average wind speed of 0.65m/s; Rectangular 4.8m × 3.4m, with an average wind speed of 2.6m/s; Rectangular 5.0m × 3.0m, with an average wind speed of 2.8m/s; Rectangular 4.5m × 2.8m, with an average wind speed of 4.8m/s.

4. Experimental Data Analysis

Four sets of experiments were completed using the above experimental methods. Surfer software was used to fit the measured data into a curve graph based on boundary conditions. Points were taken at the boundary every 50mm. The specific analysis process is as follows:

(1) 1109 ventilation tunnel, rectangular tunnel, anchor spray support, relatively flat tunnel wall, no debris inside the tunnel, tunnel width of 4.8m, tunnel height of 3.4m. After measurement, the air supply volume of the tunnel was 636.5m3/min, and the average wind speed inside the

tunnel was 0.65m/s. The monitored data was sorted out and the wind speed distribution cloud map was drawn as shown in Figure 3. The red line in the figure represents the measured average wind speed line, and the average distance from the measured average wind speed line to the roof of the tunnel is 0.3946m.

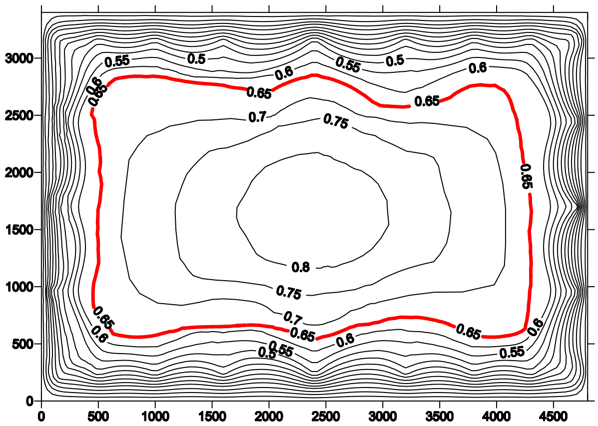

Figure 3. Cloud map of wind speed distribution in 1109 distribution lane

(2) Tail alley, rectangular alley, anchor spray support, the wall of the alley is relatively flat, there are no debris inside the alley, the width of the alley is 4.8m, and the height of the alley is 3.4m. After measurement, the air supply volume of the tunnel was 2545.9m3/min, and the average wind speed inside the tunnel was 2.6m/s. The monitored data was sorted out and the wind speed distribution cloud map was drawn as shown in Figure 4. The red line in the figure represents the measured average wind speed line, and the average distance from the measured average wind speed line to the roof of the tunnel is 0.3952m.

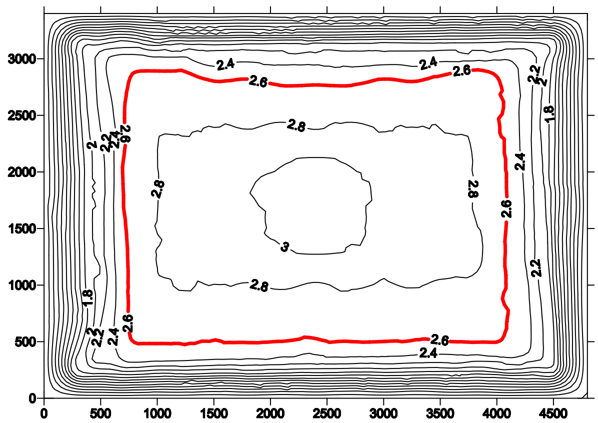

Figure 4. Cloud chart of wind speed distribution in tail lane

(3) Air distribution roadway, rectangular roadway, anchor spray support, the roadway wall is relatively flat, there are no debris inside the roadway, the roadway width is 5m, and the roadway height is 3m. After measurement, the air supply volume in the tunnel was 2520m3/min, and the average wind speed inside the tunnel was 2.8m/s. The monitored data was sorted out and the wind speed distribution cloud map was drawn as shown in Figure 5. The red line in the figure represents the measured average wind speed line, and the average distance from the measured average wind speed line to the roof of the tunnel is 0.3437m.

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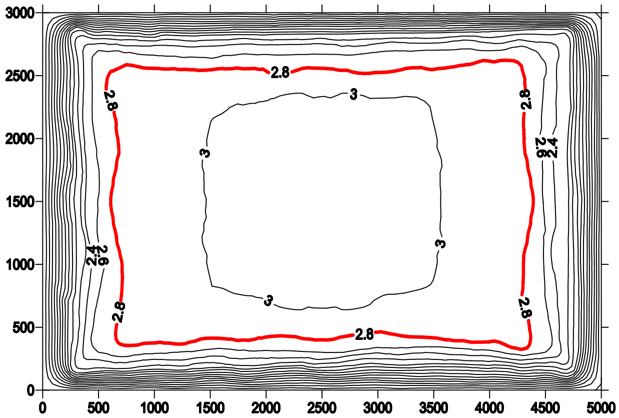

Figure 5. Cloud map of wind speed distribution in distribution alley

(4) The track roadway is a rectangular roadway with anchor spray support. The wall of the roadway is very smooth and there are no debris inside. The roadway is 4.5m wide and 2.8m high. After measurement, the air supply volume in the tunnel was 3628.8m3/min, and the average wind speed inside the tunnel was 4.8m/s. The monitored data was sorted out and the wind speed distribution cloud map was drawn as shown in Figure 6. The red line in the figure represents the measured average wind speed line, and the average distance from the measured average wind speed line to the roof of the tunnel is 0.3176m.

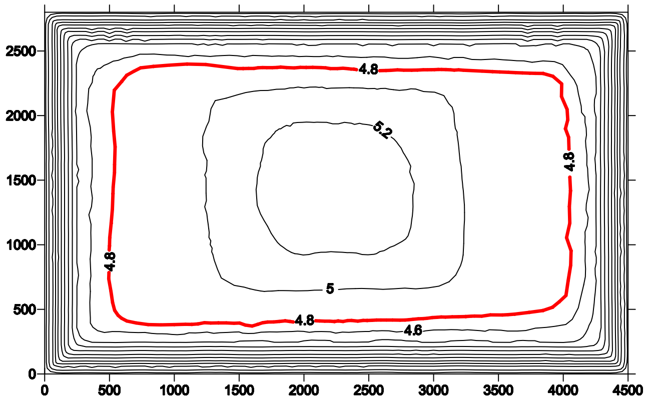

Figure 6. Cloud map of wind speed distribution in the main track roadway

From Figure 3~6, it can be seen that the contour line of wind speed at the cross-section of the tunnel is approximately rectangular, and the distribution shape of the contour line is that the central part of the tunnel cross-section expands towards the tunnel wall. The closer the wind speed contour line is to the wall of the tunnel, the denser it is, indicating a larger wind speed gradient near the wall. The sparser the wind speed contour line is to the middle of the tunnel, indicating a smaller wind speed gradient and a gradual flattening of the central wind speed in the tunnel. In the same tunnel, the higher the inlet wind speed, the smaller the thickness of the near wall velocity change layer, that is, the thickness of the boundary layer decreases with the increase of wind speed. To verify the theoretical model, a list is provided to illustrate the distance between the average wind speed line position and the tunnel roof in the measured rectangular tunnel, as well as the distance between the theoretical average wind speed line position and the tunnel roof. The errors between the two are compared, as shown in Table 1.

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Table 1. Comparison between measured values and theoretical values

Section size/(width m × height m)	Wind speed/(m/s)	Measured values /(m)	Theoretical values /(m)	Error
4.8×3.4	0.65	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%

From Table 1, it can be seen that the error between the average wind speed line positions measured in the four rectangular tunnel cross-sections selected in Sima Mine and the average wind speed line positions calculated by the theoretical model are all within 5%, indicating the reliability of the theoretical model.

5. Conclusion

(1) A calculation model for the position of the average wind speed line in a rectangular tunnel was established based on the Boussinesk theory and the Prandtl turbulence theory. The general expression for the airflow in the tunnel and the expression for the relationship between the average wind speed line and the tunnel wall were obtained.

(2) We measured the airflow field in tunnels under different wind speeds (0.65, 2.6, 2.8, 4.8 m/s) at the coal mine site, drew contour maps of wind speed distribution, and obtained the average position of the measured average wind speed line. By comparing and analyzing with the average wind speed line position obtained from the theoretical calculation model, the absolute error of the two is within 5%.

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