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Experimental Study on Wind Speed Distribution in Semi-circular Arch Tunnels Based on Mirror Stepped Grid Method

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Abstract: Ventilation is the cornerstone of coal mine safety production. Accurate monitoring of ventilation parameters is the basic guarantee for ventilation technology decision. For the problem that the accuracy of wind speed monitoring in coal mine tunnels is difficult to meet decision-making needs, a combination of theoretical calculation and experimental research was used to study the relationship between the average wind speed line and the position of the tunnel wall. The theoretical calculation obtained the expression of the relationship between the average wind speed line of the semi-circular arch tunnel section and the position of the tunnel wall. The proposed multi section mirror stepped grid format was used to investigate the airflow field in a semi-circular arch roadway under different conditions in the laboratory. The contour map of wind speed distribution was drawn, and the position of the measured average wind speed line was obtained. The absolute error between the measured average wind speed line and the theoretical model calculation results was within 5%, which verified the reliability of the theoretical calculation results.

Keywords: Mine ventilation; Wind speed distribution; Contour of wind speed; Semi circular arch roadway; Average wind speed.

1. Introduction

China's coal consumption and supply have always been among the top in the world. In recent years, with the development of the new energy industry and the environmental capacity limitations of coal, the proportion of coal in primary energy production and consumption has been decreasing year by year. However, based on the structure of China's resource production and consumption, coal resources will maintain China's position as the main energy source in the long term [1-2]. The geological storage conditions of coal in China are complex and variable, with high risk factors for various disasters, which leads to frequent accidents in mining production in engineering practice [3-5]. By summarizing past coal mine production safety accidents, the causes of most coal mine accidents are closely related to the mine ventilation system [6].

Mine ventilation is an important foundation for safe production in mines. During the excavation period of coal mine production, fresh external airflow is provided by ventilation fans or through natural ventilation to enter the coal mine tunnels, and directional and quantitative flow is carried out in the tunnel network. Finally, the polluted air is discharged from the mine, and this entire process is called mine ventilation [7-8]. When developing coal resources, it is necessary to monitor the parameters of mine ventilation in a timely manner to provide guarantees for safety, occupational health, etc. [9-11]. Therefore, all technical applications based on ventilation parameters must have reliable data assurance. In recent years, B.H. Voronin, Wang Yingmin, Ji Chaosong, Lu Guangli, and others studied the law of cross-sectional wind speed and provided a distribution function [12-14]. Zhao Dan, Shi Caixing, Sun Jiping, Pan Jingtao, and others have conducted extensive research on wind speed monitoring arrangements and measurement techniques [15-18]. Based on this, this article proposes a research method for the distribution law of wind speed in semi-circular arch tunnels based on the mirror stepped grid method. The research results can improve the accuracy of obtaining ventilation parameters such as wind speed and air volume, and directly achieve true ventilation reliability in coal mines in terms of technology and management.

2. Theoretical Model of Wind Speed Distribution in A Semi-circular Arch Roadway

The cross-section of a semi-circular arch roadway includes a rectangular section and a semi-circular section. The calculation model for the distribution law of wind speed on the cross-section of a semi-circular arch roadway is shown in Figure 1.

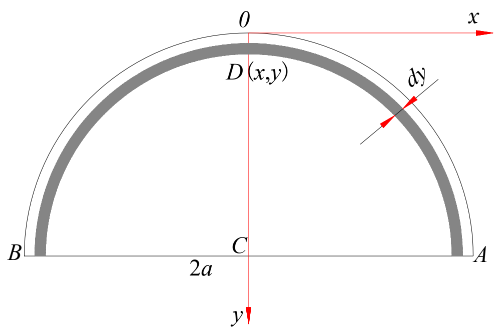

Figure 1. Calculation model for wind speed distribution on the cross-section of a semi-circular arch roadway

According to the Boussinesk theory and the Prandtl turbulence theory, an integral expression for the air flow corresponding to a semi-circular arch tunnel is established [19] as follows:

$$Q = \pi \int_0^a \left(f \ln y + C \right)\left(a - y \right) dy \tag{1}$$

The expression for the average wind speed of the semi-circular arch section in Figure 1 can be obtained from the relationship between the air volume and the cross-sectional area of the roadway:

$$\begin{aligned} \bar{v} &= \frac{Q}{A} \\ &= f \ln a - 1.5 f + C \end{aligned} \tag{2}$$

The expression for the distance y between simultaneous equations (1) and (2) is:

$$\mathrm{y} = e^{\ln a - 1.5} \tag{3}$$

Based on the calculation, obtain the general expression for calculating the air volume of a semi-circular arch tunnel and the expression for the relationship between the average wind speed line and the tunnel wall.

3. Wind Speed Measurement Method

This experiment used 16 CFD15 coal mine electronic anemometers and 16 YHC mine intrinsic safety data acquisition instruments. The ultrasonic electronic anemometer and data acquisition instrument are shown in Figure 2.

Figure 2. Anemometer

Chongqing Research Institute has constructed equipment such as induced draft devices, fan connection devices, wind measurement stations, dust measurement stations, air doors, and wind resistance adjustment devices in the existing ventilation and fire test tunnel system. The fan model used is FBCDZ№12/2×45. After renovation, a complete ventilation test system will be formed, with a total length of approximately 460 meters in the tunnel. The experimental methods for laboratory tunnels are as follows:

(1) Using a laser rangefinder to accurately measure the cross-sectional dimensions and record their support forms, while clearing obstacles inside the tunnel to ensure that the entire measurement range of the tunnel meets the measurement requirements.

(2) The symmetry of the pattern was measured by selecting half of the cross-section of the semi-circular arch roadway in the experiment. Based on the measured cross-sectional dimensions, calculate the location of the monitoring points on the cross-section. The anemometers are more dense near the wall and sparse away from the wall. Determine the specific values of measuring surface spacing l, measuring surface quantity N, measuring line height h, measuring line length L, and the number of anemometers n for each measuring line based on the size of the tunnel cross-section. According to the length L of the measuring line, the number of measuring surfaces N, and the number of anemometers n on each measuring line, assemble the anemometer installation rod and fix the anemometer on the installation rod. Based on the distance l between measuring surfaces and the distance h between measuring lines, fix the installed anemometer installation rod in the tunnel. The specific arrangement is shown in Figure 3.

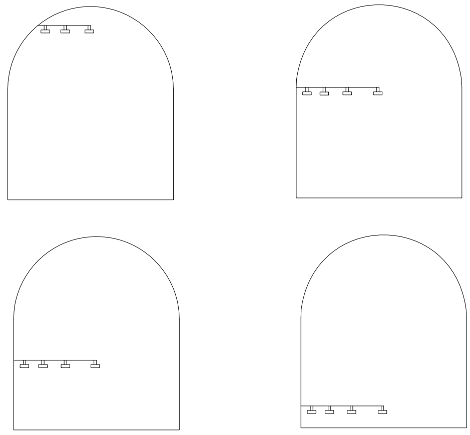

Figure 3. Installation position of each anemometer on each measuring line

(3) In this experiment, the fans were started at different operating frequencies to create different wind speed conditions in the tunnel. In this experiment, the operating frequency of the fan was adjusted four times, namely 15Hz, 20Hz, 30Hz, and 40Hz. Under the four operating frequencies, the average wind speed was measured in the experimental tunnel using the six line wind measurement method, which was 1.3m/s, 2m/s, 2.6m/s, and 3.5m/s, respectively.

(4) In this experiment, a total of 16 mining intrinsic safety data collectors were used. A ventilation parameter collector App was installed inside the mining intrinsic safety data collector and connected one-on-one to the monitoring anemometer. In order to obtain monitoring data from all anemometers at the same time, the built-in program of the ventilation parameter collector was modified to set the start time of the ventilation parameter collector, and all ventilation parameter collectors start and collect monitoring data from the anemometer at the same time. Turn on all data acquisition devices and place them at the position of the air outlet under the measured tunnel. At the same time, another data acquisition device was used to take photos and record the recorded data, ensuring the simultaneity of the obtained data.

4. Data Analysis of Laboratory Tunnels

Use Surfer software to fit the measured data into a curve graph based on boundary conditions, and take points every 50mm at the boundary. The obtained graphics are shown in Figures 4 to 7.

(1) When the starting frequency of the fan in the experimental tunnel is 15Hz, the six wire wind measurement method was used to measure the air supply of the experimental tunnel at 561.6m^3/min, and the average wind speed in the tunnel was 1.3m/s. The distribution of wind speed in the measured tunnel is 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 0.3298m.

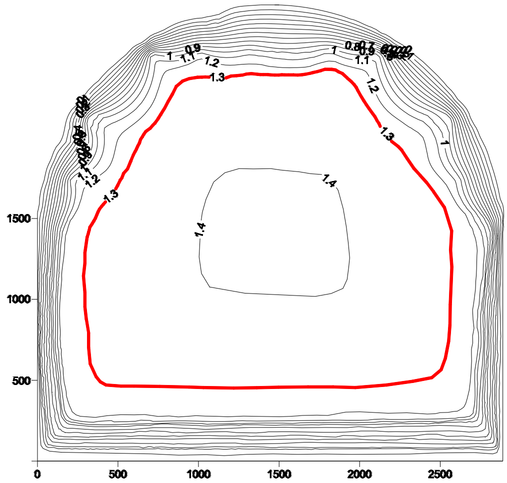

Figure 4. Wind speed distribution pattern in a semi-circular arch tunnel at a wind speed of 1.3m/s

(2) When the starting frequency of the fan in the experimental tunnel is 20Hz, the six wire wind measurement method was used to measure the air supply volume of the semi-circular arch tunnel, which is 864m^3/min, and the average wind speed of the tunnel is 2m/s. The distribution of wind speed in the measured tunnel is 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 0.3274m.

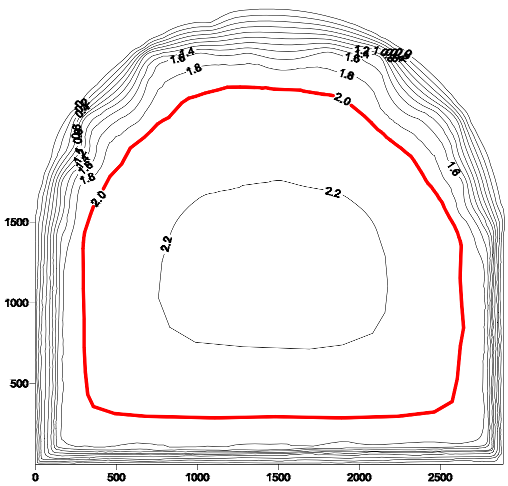

Figure 5. Wind speed distribution pattern in a semi-circular arch tunnel at a wind speed of 2m/s

(3) When the starting frequency of the fan in the experimental tunnel is 30Hz, the six wire wind measurement method was used to measure the air supply volume of the semi-circular arch tunnel, which is 1123.2m^3/min. The average wind speed in the tunnel is 2.6m/s. The distribution of wind speed in the measured tunnel is 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 0.3256m.

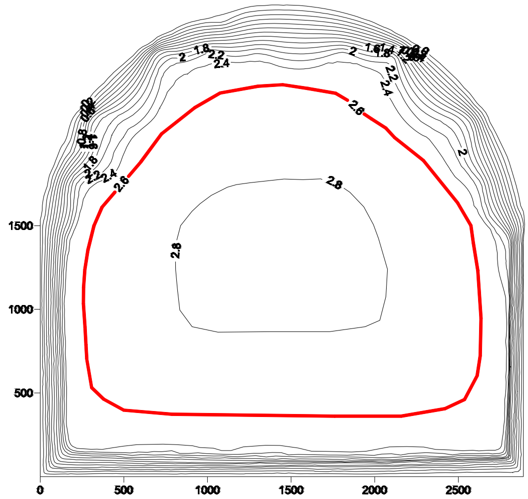

Figure 6. Wind speed distribution pattern in a semi-circular arch tunnel at a wind speed of 2.6m/s

(4) When the starting frequency of the fan in the experimental tunnel is 40Hz, the measured air supply volume in the experimental tunnel is 1512m^3/min, and the average wind speed in the tunnel is 3.5m/s. The distribution of wind speed in the measured tunnel is shown in Figure 7. 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 0.3244m.

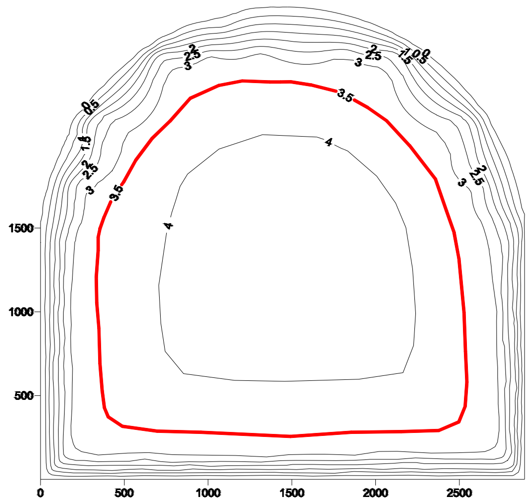

Figure 7. Wind speed distribution pattern in a semi-circular arch tunnel at a wind speed of 3.5m/s

From Figures 4~7, it can be seen that the contour line of wind speed at the cross-section of the tunnel is approximately a distribution curve with a semi-circular arch shape, and the distribution shape of the contour line is the expansion of the central part of the tunnel section towards the tunnel wall. The closer to the wall of the tunnel, the denser the wind speed contour line, indicating a larger wind speed gradient near the wall. The closer to the tunnel, the sparser the wind speed contour line, 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 low-speed area near the wall, that is, the thickness of the low-speed boundary layer decreases with the increase of wind speed. To verify the theoretical model, the table illustrates and compares the measured and theoretical values of the average distance from the position of the average wind speed line to the roof, as shown in Table 1. From Table 1, it can be seen that the error between the measured and theoretical values is within 5%, indicating the reliability of the theoretical model.

Table 1. Comparison between measured and theoretical values of the distance from the average wind speed line to the roof

Section size(width m × Height m)	Wind speed(m/s)	Actual measured value d_1 (m)	Theoretical d_2 (m)	Error $\left\|\frac{d_1-d_2}{d_2}\right\|$×100%
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%

5. Conclusion

(1) A calculation model for the position of the average wind speed line in a semi-circular arch roadway was established, and a general expression for the airflow in the roadway and an expression for the relationship between the average wind speed line and the roadway wall were obtained. The theoretical calculation results indicate that the position of the average wind speed line in the tunnel is only related to the tunnel size and is independent of other main control factors.

(2) A multi section mirror stepped grid format inspection method reflecting the distribution law of wind speed in tunnels has been proposed. With the help of high-precision anemometers, monitoring points were arranged using a stepped grid method, and the data acquisition instrument synchronously received monitoring data, achieving synchronous acquisition of monitoring data at different positions under the condition of wind speed fluctuations in the tunnel.

(3) The average measured wind speed line position under different conditions was obtained. 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%, which verifies the reliability of the theoretical calculation model and provides support for improving the effectiveness of current point monitoring.

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References

[1] Yuan Liang. Theoretical and technical thinking on the high-quality development of energy security for China's coal industry [J]. Journal of the Chinese Academy of Sciences, 2023,38 (01): 11-22.

[2] Liu Xinjie, Song Gaofeng, Jiang Binbin. Development History and Outlook of the Coal Industry [J]. Mining Safety and Environmental Protection, 2019, 46 (03): 100-103+112.

[3] Zhang Peisen, Zhang Xiaole, Dong Yuhang, et al. Analysis and Prediction of Coal Mine Accidents in China from 2008 to 2021 [J/OL]. Mining Safety and Environmental Protection: 1-6 [2023-04-28] https://doi.org/10.19835/j.issn.1008-4495.2023.02.024.

[4] Fan Chaojun, Wang Yiqi, Yang Lei, et al. Statistics and Analysis of Coal Mine Safety Accidents in China from 2012 to 2021 [J]. Mining Research and Development, 2023,43 (04): 182-188.

[5] Liu Yejiao, Yuan Liang, Xue Junhua, et al. Analysis of the occurrence patterns of coal mine gas disasters in China from 2007 to 2016 [J]. Mining Safety and Environmental Protection, 2018,45 (03): 124-128.

[6] Zhao Dan, Huang Fujun, Chen Shuai, et al. The relationship between point wind speed and average wind speed in circular tunnels [J]. Journal of Liaoning University of Engineering and Technology (Natural Science Edition), 2014,33 (12): 1654-1659.

[7] Zhang Guoshu, Tan Yunzhen, Chen Kaiyan, et al. Ventilation Safety [M]. China University of Mining and Technology Press, 2000

[8] Zhou Fubao, Wei Lianjiang, Xia Tongqiang, et al. Principles, Key Technologies, and Preliminary Implementation of Intelligent Ventilation in Mines [J]. Journal of Coal Science, 2020,45 (06): 2225-2235.

[9] Song Jialin Research on the Application of IPSO-TS Algorithm in Air Volume Optimization of Mine Ventilation Network [J]. Mining Safety and Environmental Protection, 2022, 49 (02): 78-82.

[10] Wen Tingxin, Wang Ran, Li Yinchao, et al. Evaluation of Mine Ventilation Systems Based on Attribute Mathematics Theory [J]. Journal of Liaoning University of Engineering and Technology (Natural Science Edition), 2017,36 (06): 581-585.

[11] Kobylkin SS, Kharisov AR. Design features of coal mines ventilation using a room-and-pillar development system [J]. Journal of Mining Institute, 2020,245:531-538.

[12] Yu Yuejin. Discussion on the distribution of wind speed in tunnels [J]. Journal of Huainan Institute of Mining and Technology, 1989 (01): 17-24+16.

[13] Ji Chaosong. Mathematical Model of Tunnel Ventilation Process [J]. Nonferrous Mines, 2001 (03): 1-4+8.

[14] Lu Guangli, Zhang Menghan, Fan Congqi. Analysis of fixed-point wind speed measurement method based on CFD [J]. Coal Technology, 2015,34 (05): 156-157.

[15] Zhao Dan, Zhang Hui, Zhang Na, et al. Distribution of Fault Tunnels in Mine Ventilation Systems [J]. Journal of Liaoning University of Engineering and Technology (Natural Science Edition), 2017,36 (09): 914-919.

[16] Sun Jiping, Tang Liang, Li Chunsheng, et al. The application of air volume ratio method in optimizing the layout of methane sensors [J]. Journal of Coal Science, 2008 (10): 1126-1130.

[17] Pan Jingtao, Zhao Dan, Li Zongxiang, et al. Diagnosis of fault sources and arrangement of wind speed sensors in the ventilation system of Daming Mine [J]. Journal of Coal Science, 2013,38 (S1): 153-158.

[18] Rodriguez-Diaz OO, Franco-Mejia E, Rosero E. Modeling and control of small-scale underground mine ventilation networks [J]. Ingenieria E Investigacion, 2023, 43(1): e90968

[19] Luo Guang Research on the Distribution Law of Wind Speed and Accurate Monitoring of Wind Volume in Typical Tunnel Sections [D]. Coal Science Research Institute, 2020.