LINE WIND SPEED DISTRIBUTION MODEL OF RECTANGULAR TUNNEL CROSS-SECTION

by

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Accurate monitoring of the tunnel wind speed plays a key role in achieving intelligent mine ventilation. Based on the difficulty faced in precise reflection of the average tunnel wind speed by point wind speed monitoring, this paper puts forward a method for accurate monitoring the tunnel wind speed by large-span ultrasonic linear wind speed sensor based on the method of the time difference. Besides, as to the core problem of representing the average section wind speed by section-linear wind speed, the distribution rules of section wind speed in rectangular tunnel with various support forms is studied through combing theoretical analysis and experimental verification. The results could be well applied to rapid determination of ventilation parameters in other coal mines, which is better for the ventilation management of mines.

Key words: *ventilation parameters, rectangular tunnel, wind speed, wind speed monitoring*

Introduction

Mine ventilation system, usually called as the *heart* and *artery* of the mine, serves as the most important, basic and economical technical means to ensure the safety of coalmine production [1, 2]. Accurate measurement of wind speed in tunnels plays a very important role in fault diagnosis of mine ventilation system, air-flow control and optimization and reconstruction of ventilation system [3, 4].

An air-flow velocity function of a tunnel was firstly established by Voronin based on turbulent flow formula [5, 6]. The different ideas about Voronin formula was put forward by adjusting Prandtl mixing length properly [7]. They obtained the velocity distribution function of tunnel cross-section through mathematical treatment. The linear relationship between the wind speed value at a certain point and the average value on the tunnel cross-section was explored to find that the approximate functional relationship between them through the univariate linear regression analysis [8]. They pointed out the relationship among factors, including the velocity in the tunnel section and the roughness of the tunnel, the spatial position and the average velocity [9]. The changes of turbulent boundary-layers on smooth and rough surface were studied in [10]. Gas transfer problems were solved by mathematical models [11, 12]. The air-flow velocity distribution in the cross-section of underground tunnel through on-site measurement and laboratory experiments was explored, and the relationship between the roughness of the tunnel wall surface and the wind velocity distribution was revealed in [13]. The distribution law of wind speed at the section of semi-circular arch tunnel was studied by Wei *et al*. [14] based on fluent

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simulation and field measurement. The gas control method of the long-wall working surface and the reasonable gas-flow distribution was studied in tunnels using CFD software [15].

The point wind speed sensor can only monitor the wind speed of a point on the cross-section of the tunnel. The monitoring result cannot accurately reflect the average wind speed in the tunnel [16-18], leading to large errors. It is harmful for ventilation management of the mine. In this work, we studied the relationship between the line wind speed and the average wind speed in a rectangular tunnel section. An average wind speed model was established based on the monitoring data of the line wind speed sensor.

Semi-empirical formulas of gas-flow velocity

Based on Nikuradse's experimental data and using semi-empirical formula [10], the velocity at a point in the turbulent core region can be obtained:

$$\overline{u} = U\left(2.5\ln\frac{y}{\varepsilon} + 8.5\right) \tag{1}$$

where U is the turbulent characteristic velocity, $\overline{u}$ – the point wind speed, y – the distance from the wall surface within the radius, and ε – the absolute roughness.

The average wind speed of roadway can be expressed:

$$V_{\mathrm{m}} = U\left(2.5\ln\frac{r_0}{\varepsilon} + 4.75\right) \tag{2}$$

where r_0 is the pipe radius, and V_m – the average wind speed of road way.

The maximum flow rate $V_{\max}$ can be expressed:

$$V_{\max} = U\left(2.5\ln\frac{r_0}{\varepsilon} + 8.5\right) \tag{3}$$

Based on eqs. (1) and (2), the ratio of the average wind speed of circular tube to the point wind speed in a circular tube is expressed [13]:

$$\frac{\overline{u}}{V_m} = \frac{2.5\ln\dfrac{y}{\varepsilon} + 8.5}{2.5\ln\dfrac{r_0}{\varepsilon} + 4.75} = \frac{\ln y - \ln\varepsilon + 3.4}{\ln r_0 - \ln\varepsilon + 1.9} \tag{4}$$

Analysis of wind speed distribution models

Point wind speed model

The distribution of wind speed is affected by the intersection of tunnels. In this work, field measurement of wind speed in a rectangular tunnel of Tashan mine was carried out. The following conditions are generally required for wind survey sites in the tunnels, including the stable wind speed, appropriate size, regular wall surface, without accumulation of obstacles and far away from the joints. The location of the measuring points in the 1/4 of the tunnel cross-section was shown in fig. 1. The tunnel width W = 4.94 m, the height H = 3.43 m, and the average wind speed V_m = 1.94 m/s. The wind speed values of the measuring points were shown in tab. 1.

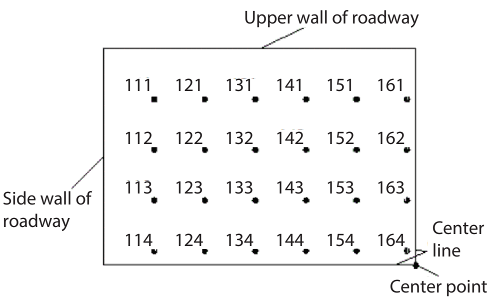

Figure 1. Lay-out chart of measuring point for wind speed

Table 1. Measurement results of point wind speed

Point number	*a*	*b*	Speed	Point number	*a*	*b*	Speed
111	0.40	0.40	1.80	113	0.40	1.20	2.26
121	0.80	0.40	2.08	123	0.80	1.20	2.31
131	1.20	0.40	2.03	133	1.20	1.20	2.19
141	1.60	0.40	2.07	143	1.60	1.20	2.23
151	2.00	0.40	2.17	153	2.00	1.20	2.21
161	2.40	0.40	2.19	163	2.40	1.20	2.20
112	0.40	0.80	2.19	114	0.40	1.60	2.21
122	0.80	0.80	2.12	124	0.80	1.60	2.27
132	1.20	0.80	2.15	134	1.20	1.60	2.35
142	1.60	0.80	2.32	144	1.60	1.60	2.11
152	2.00	0.80	2.26	154	2.00	1.60	2.23
162	2.40	0.80	2.34	164	2.40	1.60	2.27

The equivalent diameter of the interior point of the rectangular tunnel is taken to calculate the radial distance y between the measured point in the rectangular tunnel and the pipe wall. Base on the particularity of the cross-sectional shape of the rectangular tunnel and the value-taking method of the measured point value y in the velocity distribution of turbulent rough circular tubes, formula (4) is deformed into:

$$\overline{u} = \frac{\ln y - \ln \varepsilon + 3.4}{\ln r_0 - \ln \varepsilon + 1.9} V_\mathrm{m} \tag{5}$$

where W is the width of rectangular tunnel, H – the height of rectangular tunnel, a – the distance between measuring point and horizontal centerline of tunnel, and b – the distance between measuring point and vertical center line of tunnel. The relationship among a, b, W, h, and y can be given:

$$y = \frac{WH}{W + H} - 2\frac{ab}{a + b} \tag{6}$$

The wind speeds of the measured points are, respectively, calculated. The results and their fitting function were shown in fig. 2. The fitting formula:

$$\overline{u} = 0.22 \ln y + 2.15 \tag{7}$$

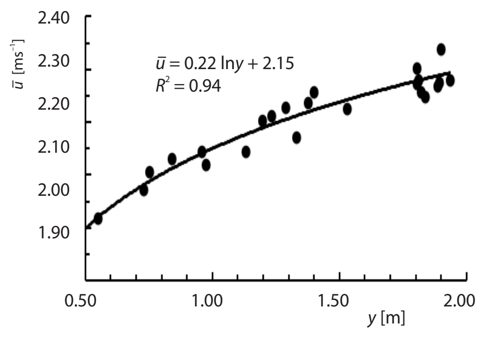

Figure 2. Point wind speed and its fitting curve

Error analysis of point wind speed model

The following was a comparison between the field measured data and the wind speed data calculated by eq. (5). It showed that eq. (5) could be better applied in the wind speed distribution of rectangular tunnel in coal mine.

Table 2. The error analysis of point wind speed in rectangular tunnel

Point number	Measured wind speed	Calculated wind speed	Error [%]	Point number	Measured wind speed	Calculated wind speed	Error [%]
111	1.80	1.92	6.53	113	2.26	2.18	3.44
121	2.08	1.99	4.38	123	2.31	2.19	5.19
131	2.03	2.06	1.43	133	2.19	2.20	0.49
141	2.07	2.13	2.96	143	2.23	2.22	0.59
151	2.17	2.21	1.77	153	2.21	2.24	1.52
161	2.19	2.30	4.83	163	2.20	2.30	4.42
112	2.19	2.07	5.62	114	2.21	2.28	3.37
122	2.12	2.09	1.22	124	2.27	2.28	0.65
132	2.15	2.13	1.07	134	2.35	2.29	2.75
142	2.32	2.17	6.55	144	2.11	2.29	8.36
152	2.26	2.22	1.70	154	2.23	2.29	2.64
162	2.34	2.30	1.87	164	2.27	2.30	1.40

The relative error between the measured and calculated, eq. (5), wind speed was listed in tab. 2. It could be seen that the relative error of most measuring points was below 5%, and that of certain measuring points was relatively large, with the maximum value of 8.36%, beyond the allowable range of engineering error. Equation (5) showed a relatively large error when used in rectangular tunnel of mine directly.

Analysis of line wind speed distribution model

The large fluctuation value of single-point wind speed makes it impossible to reflect accurately the average wind speed of the tunnel. However, the line wind speed consists of numerous continuous points, and its fluctuation range is generally small, thereby allowing it well reflect the average wind speed in the tunnel. The relationship between the line wind speed and the average wind speed of the cross-section can be written:

$$V_1 = \frac{2}{W}\int_0^{w/z} \bar{u}\mathrm{d}a = \frac{2V_m}{W(\ln r - \ln\varepsilon + 1.9}\left\{3.4 - \ln\varepsilon + b\ln\frac{(2a+W)r - 2aW}{(2a+W)r} - \right.$$
$$-\frac{1}{2}b\ln\left[\frac{W^2}{4}(r-2a) + 2a(r-1)\frac{W}{2} + a^2 r\right] + \frac{1}{2}b\ln a^2 r + \frac{b(r-1)}{\sqrt{r-(r-1)^2}}\cdot$$
$$\left.\cdot\left[\arctan\frac{W+2a(r-1)}{2a\sqrt{r-(r-1)^2}} - \arctan\frac{(r-1)}{\sqrt{r-(r-1)^2}}\right]\right\} \tag{8}$$

The following was also a comparison between the measured and calculated data by eq. (8). The lay-out chart of measuring line for wind speed was shown in fig. 3.

The relative error between the measured and calculated, using eq. (8), wind speed was listed in tab. 3. It could be seen the relative error between the measured wind speed at the measuring point and that was calculated by eq. (8). What can be found is that the relative error was less than 5%, with the maximum value of 2.54%, within the allowable range of engineering error. Equation (8) showed smaller error when used in rectangular tunnel in mine directly.

Table 3. The error analysis of line wind speed in tunnel

Point number	b	Measured wind speed	Calculated wind speed	Error [%]
L_1	0.40	2.06	2.04	0.97
L_2	0.80	2.23	2.28	2.32
L_3	1.20	2.23	2.21	0.71
L_4	1.60	2.24	2.30	2.54

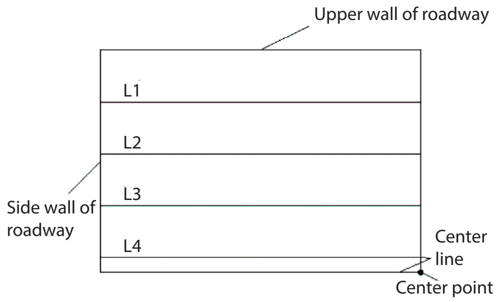

Figure 3. Lay-out chart of measuring line for wind speed

To ensure the generality of the formula, a large number of measured data of actual tunnels in Tashan Mine and Yuncheng Vocational College were selected and compared with the calculated data of eq. (8). It could be seen that the relative error was below 5%. Therefore, it could be considered that eq. (8) could be better applied in rectangular tunnels. The relative error data are shown in tab. 4.

Table 4. Relative error of line wind speed in different tunnels

Line numbers	r	b	V_1 [ms^{-1}]	V_m [ms^{-1}]	V'_m [ms^{-1}]	δ [%]
S1-1	3.75	0.20	2.86	3.30	3.27	1.61%
S1-2		0.40	3.04		3.16	1.10%
S1-3		0.60	3.08		3.04	1.00%
S1-4		0.80	3.42		3.26	1.07%
S1-5		1.00	3.37		3.12	1.96%
S1-6		1.20	3.53		3.21	0.58%
S1-7		1.40	3.61		3.23	4.08%
S2-1	4.12	0.30	3.82	4.62	4.48	3.09%
S2-2		0.60	4.29		4.60	0.41%
S2-3		0.90	4.32		4.41	4.56%
S2-4		1.20	4.62		4.56	1.27%
S2-5		1.50	4.65		4.48	3.06%
S2-6		1.80	4.68		4.42	4.37%
S2-7		2.10	4.93		4.57	1.02%

It indicated that the linear wind speed model was obviously higher in terms of accuracy and reliability through the comparisons of the two models. The value closer to the actual one could be obtained through the method of calculating the average wind speed of the tunnel by monitoring the average wind speed of a straight line in the section of the tunnel.

Value analysis of absolute roughness

The absolute roughness of coal mine tunnels is generally between 0.001 and 0.009. Equation (8) and the measured data in tab. 1 were used to calculate the relative error when the absolute roughness is 0.001~0.009. The relative error was shown in tab. 5.

Table 5. Relative error of line wind speed under different absolute roughness

Numbers		Absolute roughness									
		0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	Average
L_1	δ	1.70	0.43	0.25	0.11	0.30	0.10	0.18	0.26	1.33	0.76
L_2		0.11	0.38	0.56	0.70	0.81	0.91	0.99	1.07	1.14	0.74
L_3		1.27	1.00	0.83	0.69	0.58	0.49	0.40	0.33	0.26	0.95
L_4		2.31	2.05	1.87	1.74	1.63	1.54	1.45	1.38	1.31	1.70
Average		1.06	0.74	0.67	0.61	0.56	0.57	0.59	0.61	0.84	0.65

Table 5 showed that for mine tunnels, the absolute roughness, ε, exerted little influence on the distribution of wind speed, and the error was minimum when ε between 0.005 and 0.006 are taken. The absolute roughness ε could be taken as 0.0055 for convenience.

Conclusion

In this work, a line wind speed distribution model of rectangular tunnel cross-section was proposed based on the method of the time difference. This model was derived from previous semi-empirical formula of gas-flow in the circular pipe. It was then extended into the rectangular roadway. The extended model was verified by experimental data in the rectangular tunnel of the Tashan mine. The results could be well applied to check the rapid determination of the ventilation parameters in other coal mines.

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Nomenclature

a – distance between measuring point and horizontal centerline of tunnel, [m]
b – distance between measuring point and vertical center line of tunnel, [m]
H – height of rectangular tunnel, [m]
r – equivalent pipe radius, [m]
r_0 – the pipe radius, [m]
U – turbulent characteristic speed, [ms^{-1}]
$\overline{u}$ – the average velocity, [ms^{-1}]
V_m – average flow rate, [ms^{-1}]
$V_{\max}$ – maximum flow rate, [ms^{-1}]
V_m' – calculated average flow rate, [ms^{-1}]
V_1 – line wind speed, [ms^{-1}]
W – width of rectangular tunnel, [m]
y – distance from the wall flour within the radius, [m]

Greek symbol

ε – absolute roughness

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