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ANALYZING POINT LOCATIONS OF AVERAGE WIND SPEED IN A RECTANGULAR ROADWAY ANEMOMETER STATION USING LDA

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Abstract: Efficient and accurate measurement of mine ventilation parameters is essential for ensuring the safety of coal mines. However, the turbulent nature of airflow in underground coal mines poses significant challenges to obtaining precise measurements of parameters like wind speed. Current measurement methods in Chinese coal mines combine manual measurements and real-time monitoring with wind speed sensors. Manual measurements are labor-intensive and subject to uncertainty, while real-time sensor systems may not capture accurate average wind speeds due to improper sensor positioning. This paper addresses these challenges by using Laser Doppler Anemometer (LDA) technology to measure wind speeds in a controlled laboratory setup, avoiding interference with fluid flow.
Keywords: Mine ventilation, Wind speed measurement, Turbulence, Laser Doppler Anemometer (LDA), Ventilation management.

Introduction

Mine ventilation plays an extremely important role in safety production of coal mine. Accurate measurement of its parameters is the basic work of mine ventilation management. However, the airflow state of underground coal mine belongs to the turbulent state in most cases, and the velocity, pressure and other parameters in the flow field change very irregularly in space and time, so it is not easy to achieve its accurate measurement. At present, there are two main methods of wind measurement in coal mines in China, which are the combination of manual wind measurement and real-time monitoring of wind speed sensor. Manual wind measurement is not only time-consuming and laborious, but also has the phenomenon of "uncertainty". Although the wind speed sensor monitoring system is relatively stable, the wind speed measured by the wind speed sensor usually does not represent the average wind speed of the roadway because of its improper suspension position. It can only represent the instantaneous wind speed of a particle in the flow field. Due to the pulsation of turbulence, the real velocity of the particle constantly changes with time, which is difficult to accurately represent. Therefore, the error of replacing the average wind speed of the roadway section with the instantaneous wind speed of particles measured by the wind speed sensor is large. Literature [1,2] obtained the relationship between point wind speed and average wind speed in circular and trapezoidal roadways from the perspective of theoretical analysis. In literature [3], wind speed of circular pipe was tested by pitot tube from an experimental perspective, and the correction coefficient between point wind speed and average wind speed was given. Literature [4,5] simulated and analyzed the average wind speed of roadway from the perspective of numerical analysis. However, the above research results only provided a research method, and the research results were poor in generalization, and some formulas were not scientifically verified. In addition, pitot tube test means belong to conventional contact measuring tools, which interferes with the flow field to a certain extent, affecting the test accuracy. Moreover, the measured data only reflect the instantaneous wind speed results, and do not have time-averaged statistical significance. Laser Doppler Anemometer (LDA) as a non-contact velocity has the advantages of no interference with fluid flow, high spatial resolution and fast dynamic response, and has become an important means to study turbulence. Therefore, this paper established the experimental model of a rectangular tunnel anemometer station with smooth wall without external disturbance under laboratory conditions, and used LDA testing technology to test the wind speed of the roadway section of the anemometer station. This paper attempted to further study the distribution law of average wind speed in roadway section from the perspective of turbulence based on the statistical analysis method, and obtain the point location of average wind speed in roadway. It provides guidance for reasonably determining the location of wind speed sensor, which is of great significance for realizing intelligent and accurate ventilation management in coal mine.

1. Experimental device and measurement method

2.1. Experimental device

The experimental device is shown in Figure 1. The velocity measurement system is the three-dimensional laser Doppler velocity measurement system of Dantec Company, whose working principle is to measure the velocity of particles by using the Doppler effect principle of scattering light by moving particles [6]. Speed measuring range: -280~400m/s, speed measuring accuracy: 0.5%.

The experimental test model adopted the circulation air supply mode, which was mainly composed of the main frame (aluminum alloy), ventilation power device, air volume regulating valve, vortex flowmeter, rectifier grid, connecting pipeline and test section. According to the provisions of Coal Mine Safety Regulations [7], anemometer stations should be set up in the main underground roadways. The anemometer stations should be located in the flat roadways, the length should not be less than 4m, there should be no obstacles or bends within 10~15m before and after the tunnels, and there should be no sudden changes in the roadways, so as to ensure the wind measurement in the anemometer stations with stable air flow. Taking the actual size of horizontal vertical roadway in coal mine as an example: 50m×4m×4m(length × width × height), the experimental model is designed based on the similarity theory. The test section was a rectangular straight roadway with the dimensions of 2500mm×200mm×200mm, and the similar ratio is 1:20, as shown in Figure 2(*a*). The experimental device was made of smooth plexiglass with good light transmittance, low refractive index and eliminating boundary layer effect as far as possible, which was glued with glass adhesive to make the system airtight.

2.2. Measurement Methods

The test section was selected at a position about 6*D* from the inlet and outlet of the test section (*D* is the hydraulic diameter: 200mm), and the measuring points were arranged along the longitudinal symmetry axis of the section, as shown in Figure 2(*b*). Take the left bottom corner of the test section as the origin (0, 0, 0), the wind direction of the air flow is the *x* axis, the vertical direction is the *z* axis, and the vertical direction of the paper is the *y* axis. The spacing of the measuring point in the *z* direction was set as 4mm. A total of 49 measuring points were set, and the collection termination condition of each measuring point was 2000 samples.

In order to test the wind speed distribution of cross sections under different wind speeds, the air volume regulating valve was adjusted to make the average wind speed of cross sections *v*=1.68m/s, 2.52m/s, 3.29m/s, 4.10m/s and 4.67m/s, respectively. Cross-sectional wind speed tests were carried out at the arranged measuring points at Reynolds numbers 2.3×10^4、3.5×10^4、4.6×10^4、5.7×10^4 and 6.5×10^4. In the experiment, the specific parameters of the LDA system were set in reference[6], and the release amount of tracer particles and filter bandwidth were adjusted according to the changes of signals.

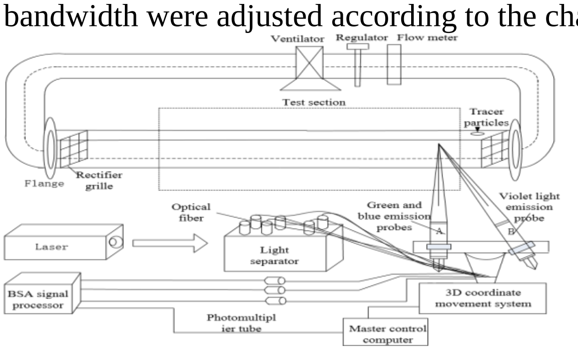
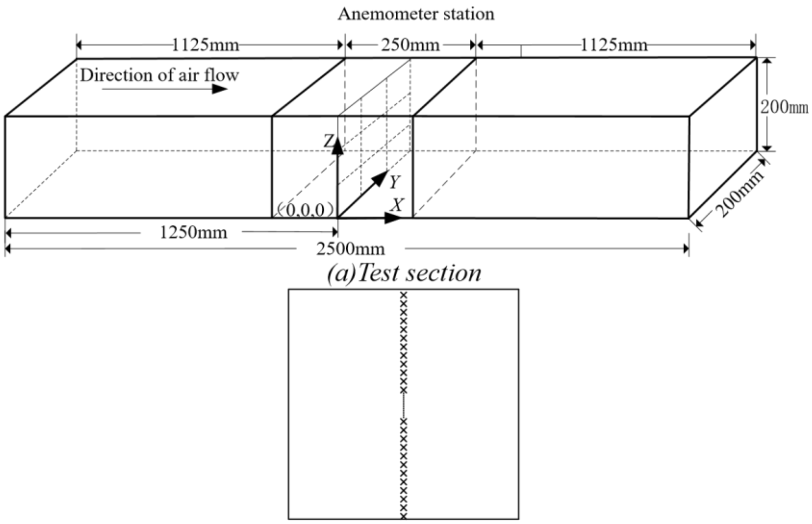


Figure 1: Experimental device of laser doppler anemometer system



(b)Measuring point arrangement (1~49 measuring points from bottom to top)

Figure 2: Model size and test area

3. Analysis of experimental results

3.1. Instantaneous wind speed distribution characteristics

The longitudinal symmetry axis of the cross-section was analyzed at the average wind speed *v*=1.68m/s and the Reynolds number =2.3×10^4, the instantaneous velocities of the first, 500th, 1000th, 1500th and 2000th particles of each measuring point were extracted and processed by Origin8.6 software. The instantaneous wind speed distribution on the longitudinal symmetry axis was obtained as shown in Figure 3 below. It can be seen from Figure 3 that the instantaneous wind speed distribution curve is extremely irregular, showing a wavy line form with different shapes. Due to the randomness and pulsation of air flow, even if the same experimental conditions are maintained, the instantaneous wind speed measured each time is different, which further indicates that the test results obtained by the traditional wind measurement method have a certain deviation from the actual. However, from the point of view of turbulence analysis, the airflow velocity field of enough times can be arbitrarily taken out for arithmetic average within a long enough time (traversal of each state of the airflow). The obtained function is consistent with the function obtained by taking any velocity field with enough times for arithmetic average. It means that the arithmetic average of any group of wind speed tends to the same definite function, which can be described by Equation (1) as follows:

$$\lim_{n\to\infty}\frac{1}{n}\sum v_i(x_1,x_2,x_3,i) = \overline{v_i}(x_1,x_2,x_3,i) \quad (1)$$

In other words, the instantaneous velocity of the airflow is a random function, but its average velocity is not. That is to say that although the turbulent pulsation is irregular and random, it has a regular statistical average result. The instantaneous random wind speed measured each time can't obtain "decisive" results, but the statistical average of a large number of wind speeds has "regular" results [8]. Therefore, the probability average method in the turbulence statistical average method is used to average a large number of experimental data, which is described as Equation (2):

$$\overline{v_i^{(p)}}(x_1, x_2, x_3,t) = \lim_{n\to\infty}\frac{1}{n}\sum_{k=1}^{n} v_i^{(k)}(x_1, x_2, x_3,t) \quad (2)$$

Where, $\overline{v_i^{(p)}}$ is the average value of random velocity according to probability; $v_i^{(k)}$ is the flow field distribution function of the *k*-th test; *n* is the number of repeated experiments.

Based on the above analysis, the wind speed data of this experiment in the mainstream *x* direction measured under different wind speeds were processed according to Equation (3). Then the velocity of particles captured by each laser beam at different times was converted into the average speed of the measuring point.

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \quad (i \quad 1,2,3\cdots 2000) \tag{3}$$

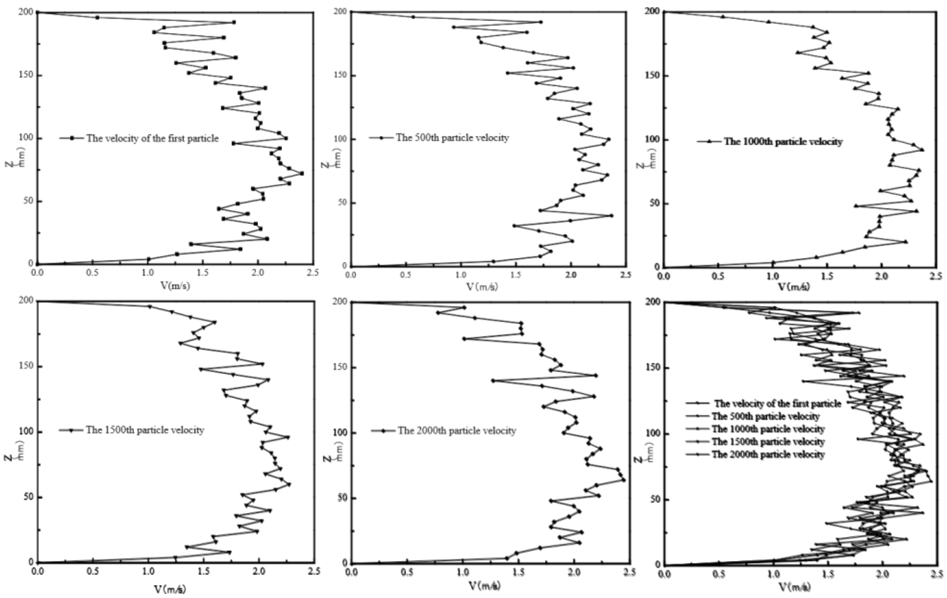


Figure 3: Instantaneous wind speed distribution

3.2. Wind speed distribution of roadway section of anemometer station based on statistical average

The wind speed distribution along the longitudinal symmetry axis of tunnel section of the anemometer station under different Reynolds numbers was obtained after averaging, as shown in Figure 4. The wind speed distribution curve with good regularity in Figure 4 is smoother than the instantaneous irregular distribution curve in Figure 3. From the distribution trend, the smaller the average wind speed is, the flatter the wind speed distribution curve on the axis is. The larger the average wind speed, the fuller the wind speed distribution curve on the axis. The wind speed value is relatively high in the central area and gradually decreases from the center to the side wall. The distribution area of average wind speed under different ventilation wind speeds is close to the side wall of the roadway.

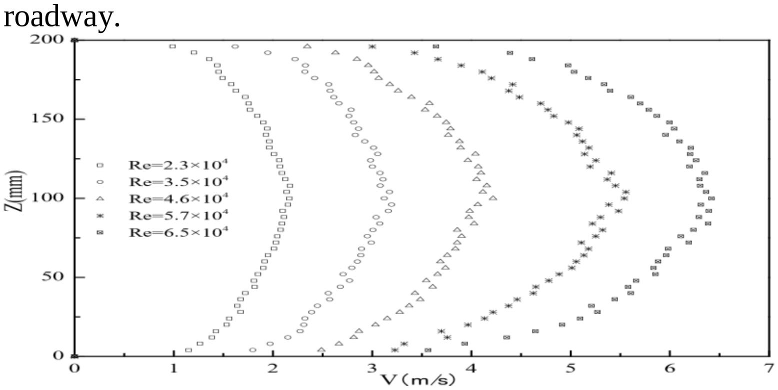


Figure 4: Wind speed distribution of the section on the horizontal axis

3.3. Point distribution of average wind speed in roadway section of anemometer station

In order to further obtain the point distribution law of average wind speed in cross-section, dimensionless analysis method was introduced [9]. The height (Z)was taken as the dimensionless scale of the measuring point from the side wall of the roadway, and the average speed of the section(v) was taken as the dimensionless scale of the velocity. The definition $z^+ = z/Z$ was the dimensionless distance, and z was the distance between the measuring point inside the section and the wall. $v^+ = v_i / v$ was the dimensionless velocity, v_i (i =1,2,3……49)was the velocity of the measuring point in the cross-section, and the wind velocity distribution and fitting curve of the cross-section under different Reynolds numbers were obtained, as shown in Figure 5, and the fitting function was shown in Table 1. It should be noted that the fitting curve of wind speed distribution in this experiment was analyzed from the data of measuring points 4mm away from the wall, and the viscous bottom layer and transition region of solid wall turbulence were not involved. The main reason is that the solid wall shear turbulence is divided into viscous bottom zone, transition zone and turbulent core zone, while the viscous bottom flow is laminar flow state, and laminar sublayer and transition zone are very small. Therefore, when calculating the mean wind speed, the velocity distribution profile in the mainstream core turbulent zone can be used instead of the real profile, and the errors generated can be ignored [10].

The average wind speed v=1.68m/s, 2.52m/s, 3.29m/s, 4.10m/s and 4.67m/s were substituted into the fitting curve in Table 1, and the specific locations of the average wind speed points were obtained as shown in Table 2. It can be seen that the position of the average wind speed is not completely symmetric in the distance from the upper and lower walls, which may be due to the deviation of small distance caused by the experimental test error. However, the maximum deviation is only 0.0192Z, which has little influence on the wind speed distribution in the section and can be approximately ignored. Therefore, it can be considered that the average wind speed position is roughly the same distance from the upper and lower walls, which has symmetry. According to the magnitude of each correlation coefficient, the closer it is to 1, the closer the data fitting is to the measured true value. Under the Reynolds number of 2.3×10^4、3.5×10^4、4.6×10^4、5.7×10^4 and 6.5×10^4, the ratio of the vertical distance between the average wind speed point and the side wall is about 0.17, 0.15, 0.14, 0.11 and 0.08. It can be seen that under different wind speeds, the locations of the average wind speed values are close to the side wall of the roadway, and with the increase of the average wind speed, the distance between the location and the side wall is basically unchanged. Therefore, according to the specific position of the average wind speed point in the roadway, the layout position of the wind speed sensor can be determined, and the continuous wind speed collection can be carried out. The average value of each state of the air flow after traversing is the average wind speed of the section.

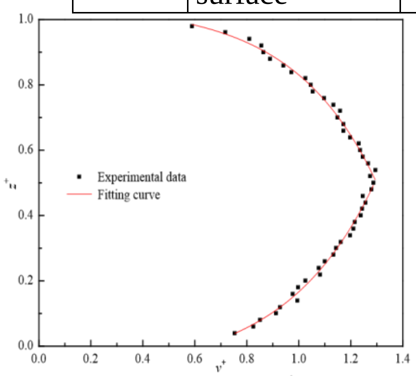
Table 1: Fitting function of the wind speed distribution

Reynolds number	Fitting function			
	$0.02 \le z^+ \le 0.5$	Correlation coefficient	$0.5 \le z^+ \le 0.98$	Correlation coefficient
2.3×10^4	y= 0.0822+ 0.01342e2.9195x	0.99118	y =1.04414 0.0094e−3.1207x	0.99069
3.5×10^4	y= 0.13498+ 0.02004e2.6667x	0.98254	y =1.02934 0.00632−e3.3676x	0.97579
4.6×10^4	y= 0.10844+ 0.01047e3.1933x	0.97351	y=1.04757 0.00514−e3.6407x	0.9844

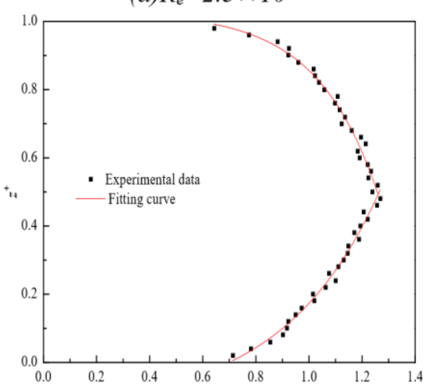
5.7×10^4	$y= 0.04579+ 0.00464e3.5427x$	0.98074	$y=1.03539\ 0.00323-e^{3.7763x}$	0.9854
6.5×10^4	$y= 0.01802+ 0.00136e4.3037x$	0.9828	$y = 0.9824\ 0.000091-e^{6.2216x}$	0.98092

Table 2: The location of average wind speed point

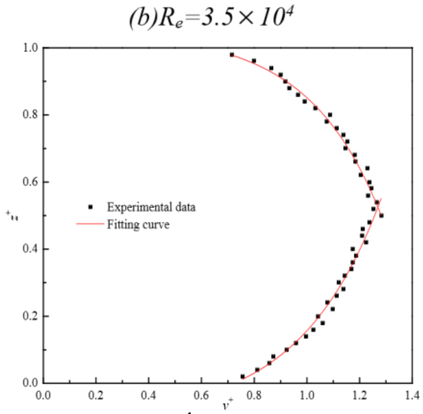
Reynolds number		2.3×10^4	3.5×10^4	4.6×10^4	5.7×10^4	6.5×10^4
Average wind speed $m\cdot s^{-1}$		1.68	2.52	3.29	4.10	4.67
Position	Away from the lower wall surface	0.1665Z	0.1535Z	0.1467Z	0.1146Z	0.0826Z
	Away from the upper wall surface	0.1689Z	0.1540Z	0.1484Z	0.1056Z	0.0634Z



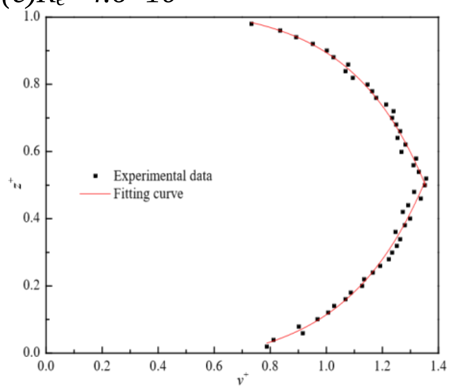
(a)R_e=2.3× 10^4

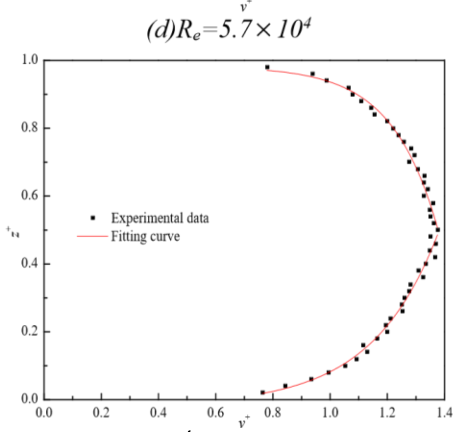


v+



(c)R_e=4.6×10^4





(e)R_e=6.5×10^4

Figure 5: Fitting curve of the wind speed distribution

4. Conclusion

When the Reynolds number ranges from 2.3×10^4 to 6.5×10^4 the instantaneous wind speed distribution at the roadway section of the anemometer station presents irregular wavy distribution. Even if the same experimental conditions are maintained, the instantaneous wind speed measured each time is different, which indicates that the test results obtained by the traditional wind measurement method have certain deviation from the actual.

Although the instantaneous velocity of the roadway air flow is irregular and random due to the turbulent pulsation, it has certain regular statistical average results. Based on the turbulence statistical average, the cross-section distribution curve of the tunnel is smooth, and the wind speed is larger in the center area, and gradually decreases from the center to the side wall.

When the Reynolds number ranges from 2.3×10^4 to 6.5×10^4， the wind speed distribution of the section conforms to the exponential function form, and the ratio of the vertical distance between the average wind speed point position to the side wall and the side length is basically unchanged. The dimensionless analysis method is introduced to make the experimental results have strong generalization significance. For any rectangular roadway, the layout position of the wind speed sensor can be determined by the reverse calculation of the determined average wind speed point. The instantaneous wind speed is continuously collected and its average value is the average wind speed of the roadway section.
The traditional wind measurement principle and method can only meet the general engineering needs, but can't reflect the turbulent pulsation characteristics of underground air flow. LDA testing technology can accurately test the turbulent characteristics of roadway flow field, and provide basic parameters for the determination of average wind speed point location in underground anemometer stations and the development of intelligent wind measuring instruments.

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