Simulation and experimental study on the airflow distribution in rectangular cross-section tunnels

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Abstract. Ventilation is quite important for mine safety. The airflow behavior and the influence of the ventilation parameters on the airflow distribution in rectangular tunnels were investigated by experimental and simulation methods. Then the relationship between the distribution feature of the average velocity and the parameters of tunnel cross-section was analyzed quantitatively by mathematical method. The results showed that the average velocity points show a continuous circular distribution and the simulation results were in accordance with the experimental results. The shape of cross-section is the critical factor influencing airflow behaviour, and the ventilation velocity had little influence on the distribution of the average velocity points. In the region where the velocity was larger than the average velocity, the velocity gradient was small, and as the distance to the wall increased, the velocity increased slowly. While in the region where the velocity was smaller than the average velocity, the velocity gradient was large, and the velocity changed more quickly. Based on the simulation and experimental data, a group of the characteristic equations were developed and the location of the average velocity can be obtained conveniently while the dimension of the tunnel was known.

1. Introduction

Ventilation system is the basic and important system in mines. According to the related statistics, quite a lot of mine disasters like gas explosion, dust explosion occurred due to bad ventilation in mines. Therefore, it was quite necessary and important for mines safety to study on the ventilation especially the accurate measurement of the airflow volume in tunnels.

A number of studies have been carried out on the airflow behavior in underground mine tunnels[1,2], but the distribution of the average airflow velocity was not analyzed in the above studies. Studies conducted by M.T. Parra et al., Chen and Yu, Isidro Diego et al. got the airflow distribution of different cross-sections by CFD method[3-5]. However, the relationship between the average velocity and the shape of the cross-sections was not analyzed further.

Some researchers have analyzed the velocity distribution in tunnels with rectangular cross-sections and have developed a formula to describe the relations between the air flow velocity and the dimensions of the tunnel cross-section. However, the formula was not quite accurate and the calculation still needed some parameters that only can be obtained by experiments or on site testing[6-9]. In some recent studies, Ding Cet al. analyzed airflow distribution in mine tunnels by experimental and CFD methods, and the characteristic equations of average velocity distribution have been developed in trapezoidal cross section tunnels and three-center arch section tunnels respectively[10-12].
According to the above-mentioned studies, the airflow distribution in different cross-section tunnels has not been described clearly, and the relationship between the average airflow velocity and the tunnel dimensions were not developed fully. Therefore, it is still necessary to study on how to get the location of the average airflow velocity in tunnels.

The paper aimed to analyze the airflow distribution in mine tunnels with rectangular cross-section by experimental and simulation methods. Furthermore, based on the analysis on the relationship between the average airflow velocity and the dimensions of the rectangular cross-section, the characteristic equations were expected to developed to describe the location of the average airflow velocity in tunnels.

2. Airflow Experimental Measurements

2.1 The experimental system
Based on the real mine tunnels, the ventilation experimental system was designed as shown in figure 1. The experimental system was consist of a fan, a flowmeter, the tunnel with dimension sizes of 6000*200*200mm, a high-precision micromanometer, a Pitot tube. The fan was the power machine which can generate fresh air and the flowmeter was used to adjust the airflow volume into the tunnel model so as to simulated different ventilation conditions in the tunnel. The high-precision micromanometer and the Pitot tube were used together to measure the airflow velocity of any point in the tunnel.

![Figure 1. The ventilation experimental system](image)

2.2 Experimental methods
According to the Coal Mine Safety Regulations in China, the ventilation velocity in the mine tunnels was generally between 0.15m/s and 8m/s, so the ventilation velocities of 2m/s, 4m/s in the experimental tunnel were set so that the airflow volume were 0.08m$^3$/s, 0.16m$^3$/s, respectively. In this experiment the measured cross-section was set to be 5.6m from the tunnel inlet where the airflow was fully developed. The measured cross section of tunnel was divided into 400 small square sections. The airflow velocity was measured in the center of each small square section.
2.3 Experimental results

The average airflow velocity in experimental tunnel was 2m/s, 4m/s respectively. The velocity on the measured cross-section was measured at each measured point at four different airflow volumes as shown in Fig.2

![Velocity contour map at different ventilation velocities](image)

It can be seen from Figure 2 that at each ventilation velocity, the airflow feature on the measured cross-section showed like a group of rings which were similar with the rectangular tunnel. The airflow distribution was affected by the tunnel shape. The airflow velocity increased from the tunnel wall to the tunnel center on the cross-section and got its maximum value in the tunnel center.

3. Validation

To validate the CFD results, the geometric model in this simulation was set to be the same as the experimental tunnel model. The Computational Fluid Dynamics commercial software was used to model the airflow behavior. The choice of turbulence model is based on the previous researches, the Standard k-epsilon turbulence model provides better results when simulating the tunnel airflow[13-18].

When developing the mathematical model, the following assumptions were made: the airflow was incompressible, the wall was adiabatic, and there were neither workers nor vehicles in the tunnel, and the presence of smoke and dust was ignored.

The computational domain was characterized by an airflow at 25°C. The tunnel inlet was set to be the velocity-inlet and the airflow velocity was set to be 2 and 4 m/s, respectively. The tunnel outlet was set to be the pressure-outlet. The average velocity distribution measured by the experiment and predicted by the simulation, on the cross-section located 5.6m from the tunnel inlet and at different ventilation velocities, was compared further, as shown in Figure 3.
A good correlation can be observed from Figure 3 between the measured and predicted results for the average airflow velocity curve at different ventilation velocities, so the CFD simulation method was accurate enough to simulate the airflow behavior in tunnels.

4. CFD Modelling of airflow 4behavior

In order to analyze the average velocity distribution on the rectangular cross-section quantitatively and develop the relationship between the average velocity and the cross-section sizes, the model in Figure 2 was amplified to 2 and 3 times respectively so that model 1, model 2 and model 3 can be obtained. The average velocity distribution on fully developed turbulence cross-sections was studied. In this paper, the distance between the cross-section was analysed, and the tunnel inlet was set to be 5.6m(Z₁), 11.2m(Z₂), 16.8m(Z₃) respectively according to fluid mechanics theory. The average velocity contour map on the above five cross-sections were analysed as shown in Figure 4.

4.1 Average velocity contour map on rectangular cross-sections

Figure 4 showed the mentioned average velocity distribution at different ventilation velocities and different tunnel sizes.

(a) Average velocity distribution of model 1 on Z₁
(b) Average velocity distribution of model 2 on Z₂
It can be seen from Figure 4 that as to each tunnel model, all the average velocity contour map at different ventilation velocities coincided with each other perfectly. That means the airflow velocity in the tunnel had little influence on the above distribution feature. In addition, for different tunnel models, with the sizes increased, the location of the average velocity contour map was increased but the average velocity distribution still showed circular distribution. And that means the average velocity distribution especially its location was related to the cross-section sizes.

4.2 Analysis of the average velocity distribution

In order to further analyze the distribution of the average velocity points and develop its characteristic equations, the distribution curve has been separated into eight parts as shown in Figure 5.

According to Figure 5, it can be seen clearly that the curve was symmetrical, so the feature of the fifth, sixth and seventh parts were analyzed quantitatively.

(1) The fifth part

Based on analysis of relationships between the length of the fifth part, the width of the tunnel and the distance from the tunnel floor to part 5, it has been found that the length of the fifth part and the distance from the roadway floor to part 5 had perfect linear relations with the width of the roadway respectively, as shown in Figs.6 and 7.
Based on the above analysis, the characteristic equations of the fifth part can be described as equations (1) and (2).

\[ a_1 = 0.089a + 0.0012 \quad (1) \]
\[ a_2 = 0.2876a + 0.0144 \quad (2) \]

Where \( a \) is width of the tunnel, m; \( a_1 \) is distance between the fifth part curve and the tunnel floor, m; and \( a_2 \) is length of the fifth part curve, m.

(2) The sixth part

Numerical fitting methods have been used to develop the characteristic equations of the sixth part. The characteristic equations of the sixth part in five tunnels are shown in table 1.

| The width of tunnel \( a \) (m) | Fitting equations of the sixth part | \( R^2 \) |
|-------------------------------|-----------------------------------|--------|
| Model 1 0.2                  | \( y = 0.0014x^{0.9911} \)       | 0.9823 |
| Model 2 0.4                  | \( y = 0.0054x^{0.9891} \)       | 0.9783 |
| Model 3 0.6                  | \( y = 0.012x^{0.9911} \)       | 0.9823 |

By combining the above five equations and the width of different tunnels, the five equations can be normalized into one equation, as equation (3).

\[ y = 0.0328a^{1.9633}x^{-1} \quad (3) \]

Where \( a \) is width of the tunnel, m; \( x \) is \( x \)-coordinate, m, and \( x \in [0.089a + 0.0012, 0.3562a - 0.0072] \); and \( y \) is \( y \)-coordinate, m.

(3) The seventh part

The seventh part and fifth part are symmetrical for \( y = x \), so the seventh part can be described as equation (4).

\[ y = 0.089a + 0.0012 \quad (4) \]

Where \( a \) is width of the tunnel, m; \( x \) is \( x \)-coordinate, m, and \( x \in [0.3562a - 0.0072, 0.6438a + 0.0072] \); and \( y \) is \( y \)-coordinate, m, and \( y \in [0.3562a - 0.0072, 0.6438a + 0.0072] \).

Based on the above analysis, the characteristic equations of all the eight parts have been developed as shown in Table 2.
Table 2. Characteristic equations of the average velocity distribution in rectangular cross-section tunnels.

| Part number | Characteristic equation | Range of parameters |
|-------------|-------------------------|---------------------|
| 1           | $f(x) = 0.911a - 0.0012$ | $x \in [0.3562a - 0.0072, 0.6438a + 0.0072]$ |
| 2           | $f(x) = a - 0.0328a^{1.9633}(a - x)^{-1}$ | $x \in [0.6438a + 0.0072, 0.911a - 0.0012]$ |
| 3           | $x = 0.911a - 0.0012$ | $y \in [0.6438a + 0.0072, a]$ |
| 4           | $f(x) = 0.0328a^{1.9633}(a - x)^{-1}$ | $x \in [0.6438a - 0.0072, 0.911a - 0.0012]$ |
| 5           | $f(x) = 0.089a + 0.0012$ | $x \in [0.9633, 1]$ |
| 6           | $f(x) = 0.0328a^{1.9633}x^{-1}$ | $y \in [0.3562a - 0.0072]$ |
| 7           | $f(x) = 0.089a + 0.0012$ | $y \in [0.3562a - 0.0072, 0.6438a + 0.0072]$ |
| 8           | $f(x) = a - 0.0328a^{1.9633}x^{-1}$ | $x \in [0.089a + 0.0012, 0.3562a - 0.0072]$ |

5. Conclusions
The aim of this work was to demonstrate the airflow behaviour in tunnels by experimental and simulation methods and develop the characteristic equations to describe the relationship between average velocity distribution and the cross-section parameters.

The airflow distribution showed circular distribution which was similar to the shape of rectangular cross-section at different ventilation velocities and cross-section sizes. The shape of the cross-section was the critical factor influencing the airflow distribution. The airflow velocity reaches its maximum value in the center of the roadway and decreases from the center to the tunnel wall.

The average velocity points were mainly close to the wall at different ventilation velocities. In the region where the velocity was larger than the average velocity, the velocity gradient was small, and as the distance to the tunnel wall increased, the velocity increased slowly. While in the region where the velocity was smaller than the average velocity, the velocity gradient was large, and the velocity changed more quickly. The tunnel wall is also a critical factor influencing the airflow distribution.

The ventilation velocity has little influence on the average velocity distribution. Characteristic equations were developed to describe the average velocity distribution, and once the tunnel sizes were known, the location of the average velocity was obtained easily by these equations, which can provide theoretical guidance for accurately measuring the average velocity and ventilation airflow volume in mine tunnels.

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