International Journal of Mining Science and Technology 27 (2017) 663–667

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Numerical simulation of airflow distribution in mine tunnels

Ding Cui [a,*], He Xueqiu [b,c], Nie Baisheng [c]

[a] Department of Safety Engineering, China University of Labor Relations, Beijing 100048, China
[b] School of Civil and Environment Engineering, University of Science and Technology Beijing, Beijing 100083, China
[c] School of Resource & Safety Engineering, China University of Mining & Technology, Beijing 100083, China

ARTICLE INFO

Article history:
Received 1 November 2016
Received in revised form 18 December 2016
Accepted 23 January 2017
Available online 29 May 2017

Keywords:
Mine tunnel
Turbulence
Airflow distribution
Three-center arch
Average velocity

ABSTRACT

Based on 3D modelling of typical tunnels in mines, the airflow distribution in a three-center arch-section tunnel is investigated and the influence of air velocity and cross section on airflow distribution in tunnels is studied. The average velocity points were analyzed quantitatively. The results show that the airflow pattern is similar for the three-center arch section under different ventilation velocities and cross sectional areas. The shape of the tunnel cross section and wall are the critical factors influencing the airflow pattern. The average velocity points are mainly close to the tunnel wall. Characteristic equations are developed to describe the average velocity distribution, and provide a theoretical basis for accurately measuring the average velocity in mine tunnels.

1. Introduction

Mine ventilation is the process of continually inputting fresh air and outputting polluted air. The ventilation system is the basic system in mines. It is estimated that many mine disasters, including fire, coal gas and dust explosions, occur because of failures of the ventilation systems [1].

Nowadays, the airflow velocity and volume in tunnels are detected by on-line monitoring systems. However, because of the non-uniform distribution of airflow, the velocity measured by sensors is not the average velocity in section. As such, it is quite necessary to study the airflow pattern especially the average velocity distribution to calculate the airflow volume accurately. At present, the airflow distribution on the cross-section is macroscopically described with numerical simulation in several studies [2–5]. Only a few have studied the average velocity distribution in circular and rectangular tunnels quantitatively, by experimental and theoretical methods [6–11]. However, the relations between the airflow distribution, the average velocity and the cross-sectional shape and size have not been developed and described successfully. The characteristic equations of average velocity distribution close to the roof have been developed in three-center arch section tunnels and trapezoidal cross section tunnels [12,13]. But the other areas of the average velocity distribution on three-center arch section were not developed quantitatively. Thus, this study aims to present the airflow distribution and develop the characteristic equations of the average velocity distribution in three-center arch section tunnels.

2. Numerical simulation

2.1. Physical model of the tunnel

The numerical analysis method, which is proven to be accurate enough by experiments in the previous study, was adopted to simulate the airflow distribution in three-center arch section tunnels [12]. In this paper, the tunnel length is 8 m, the width is 260 mm, and the wall height is 113 mm. The small arch radius is 66 mm, and the large arch radius is 183 mm, as shown in Figs. 1 and 2.

To analyze the airflow distribution in tunnels quantitatively, the model in Fig. 1 is amplified to 2, 3, 4 and 5 times respectively. The sizes of the five three-center arch section tunnels are shown in Table 1. The airflow in the tunnels was set to be turbulent, which is like actual ventilation conditions. The airflow distribution was then studied under different airflow velocities and different tunnel sizes.

2.2. Mathematical model and assumptions

Per the fluid dynamics theory, the airflow in tunnels can be described by using the following equations:

* Corresponding author.
E-mail address: cui_ding@163.com (C. Ding).

http://dx.doi.org/10.1016/j.ijmst.2017.05.017
2095-2686/

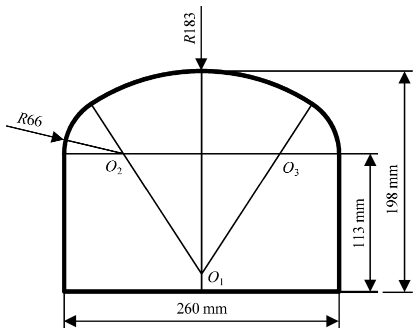

Fig. 1. Three-center arch-section of the physical model.

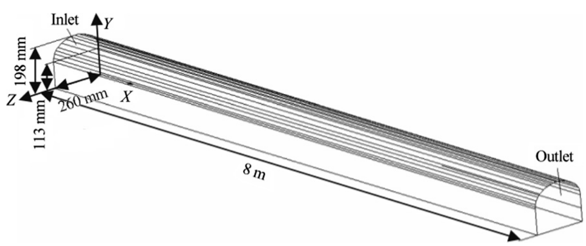

Fig. 2. Physical model of the tunnel.

The continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = 0 \tag{1}$$

The momentum equations (i direction)

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(u_j u_i)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(u\frac{\partial u_j}{\partial x_j}\right) \tag{2}$$

The energy equation

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho u_j h)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma_h \frac{\partial h}{\partial x_j}\right) \tag{3}$$

The standard $k-\varepsilon$ model was used to calculate the turbulence and diffusion of the airflow.

k equation

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon - Y_M \tag{4}$$

ε equation

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + G_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{5}$$

In the above-mentioned equations, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients,

$$G_k = -\rho\overline{\mu_i'\mu_j'}\frac{\partial \mu_j}{\partial x_i} \tag{6}$$

where Y_M is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, and $Y_M = 2\rho\varepsilon M_t^2$; and μ_t the turbulent viscosity, and $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$.

$C_{1\varepsilon}$, $C_{2\varepsilon}$ and C_μ are constants. $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_\mu = 0.09$. σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively. $\sigma_k = 1.0$, and $\sigma_\varepsilon = 1.3$. ρ is the density in kg/m^3. u is the velocity, m/s. k is the turbulence kinetic energy, kJ/kg. ε is the turbulence kinetic energy dissipation rate in m^2/s^3. μ is the molecular (dynamic) viscosity, Pa·s. t is the time, s, and h is the static enthalpy, k. Γ_h is the transport coefficient.

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

2.3. Boundary conditions and parameters

The tunnel inlet was set to be the velocity-inlet and the airflow velocity was set to 1, 2, 3, 4 and 5 m/s respectively. The tunnel outlet was set to be the pressure-outlet and the relative pressure was 0 Pa. The airflow distribution in the three-center arch section tunnels of five sizes were simulated under the different airflow velocities.

3. Analysis of the airflow pattern in tunnels

The airflow distribution on fully developed turbulence cross sections were studied. In this paper, the distance between the cross sections analyzed and the tunnel inlet was set according to fluid mechanics theory. The distance between the cross sections analyzed and the tunnel inlet was 5.6(Z_1), 11.2(Z_2), 16.8(Z_3), 22.4(Z_4), 28(Z_5) respectively. The velocity profiles on the above five cross sections (Z_1, Z_2, Z_3, Z_4, Z_5) were analyzed as shown in Fig. 3.

It can be concluded from Fig. 3 that the airflow distribution shows a circular distribution which is like the shape of three-center arch section under different ventilation velocities and cross section sizes. The shape of the cross section was the critical factor influencing the airflow pattern. The airflow velocity reached its maximum value in the center of the tunnel and decreased from the center to the tunnel wall. The average velocity points were mainly close to the tunnel wall under different airflow velocities and the airflow velocity which was smaller than the average velocity would decrease more quickly when it was closer to the tunnel wall. According to the above analysis, the tunnel wall is also a critical factor influencing the airflow distribution.

4. Analysis of average velocity distribution

The average velocity points are quite critical to achieve an accurate measurement and monitoring of ventilation volumes in tunnels. According to Ding, the distribution of the average velocity points in any three-center arch section tunnel shows as an annular ring and the ventilation velocity has little influence on the above distribution feature[12]. In order to further analyze the

Table 1
Dimensions of three-center arch tunnels.

Tunnel number	Tunnel parameter				
	Large arch radius (mm)	Small arch radius (mm)	Width (mm)	Wall height (mm)	Length (m)
1	183	66	260	113	8
2	366	132	520	226	16
3	549	198	780	339	24
4	732	264	1040	452	32
5	915	330	1300	565	40