Study on the Characteristics of Flow Field and Gas Migration in Gas Tunnels

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Abstract. In order to improve the ventilation efficiency and gas dilution effect in the gas tunnel, the main source and formation mechanism of the gas in the tunnel were analyzed, and the hydrodynamic calculation model is established for the gas tunnel ventilation with the auxiliary vertical shaft. The $k-\varepsilon$ two-equation turbulence model was used to simulate the ventilation effect under different wind velocity, the flow field distribution characteristics and gas migration regularity under the auxiliary ventilation conditions were obtained. The results indicate that the internal space of the tunnel can be divided into different zones in the longitudinal direction according to the distribution characteristics of the flow field in the tunnel. The distribution of gas concentration in the tunnel is closely related to the flow field characteristics of each zone. The ventilation of the gas tunnel must meet both the requirements of the gas concentration dilution and the cross section wind velocity. When the cross section wind velocity is greater than 0.5 m/s, the airflow reaches full turbulence state in tunnel. There is obvious effect on eliminating accumulation of gas at the top of the tunnel by the cross section wind velocity controlling. Under the condition of cross-section wind velocity is 0.5~1.0 m/s, the methane zone is prone to accumulate at the top of the tunnel, which can be diluted when the cross-section wind velocity is greater than 1.0 m/s.

1. Introduction
Tunnel gas is one of the major geological disasters in tunnel construction. The main causes of gas disasters are suffocation, explosion, coal and gas outburst, in which the gas explosion happens most likely and its damage is the most serious [1]. The gas content in the tunnel is generally lower than that of coal mines, but once occurred, the consequences are often very serious, causing major personal injury and death and huge economic losses.

Numerous research on the distribution of wind flow field [2], gas formation mechanism, gas prediction model [3], gas distribution characteristics [4], gas controlling [5] and ventilation technology in tunnels were carried out by research institutions and scholars from all over the world [6, 7].

Zhang studied the macroscopic characteristics of non-coal gas structures in Longquanshan tunnel, analyzed the engineering characteristics of gas occurrence, and carried out the prediction and evaluation of gas occurrence and protection level [8]. Zeng established a three-dimensional model and carried out numerical simulation calculation. Through the study of gas volume fraction distribution in each area of the tunnel, the characteristics of gas distribution inside the tunnel were analyzed, and the distribution regularity of gas volume fraction in tunnel was obtained [9]. Based on the study of many
gas tunnels, Kang summed up three genetic types of gas tunnels in non-coal strata [10]. By means of numerical simulation, the migration of gas in surrounding rock was studied by Zhang. The distribution of gas emission at different locations in the shale formation tunnel is studied, and the prediction method of gas emission in the tunnel of shale lot was explored [11]. In order to study the regularity of gas migration in tunnel and its influence on non-rail transportation tunnel under construction, numerical simulation is carried out to study the distribution regularity of gas emission from excavation face of Tianping tunnel on Chongqing-Guiyang railway [12]. Through relevant research at home and abroad, it is known that a lot of research result on the construction technology of gas tunnels have been achieved, but the regularity of the flow field under the condition of auxiliary ventilation with a vertical shaft are not clear. The concentration distribution regularity and migration characteristic of gas under various complicated conditions remains to be further studied.

For high concentration gas tunnels, it is recommended to use the roadway ventilation by relevant specifications, but there is no clear regulation for the auxiliary ventilation with the vertical shaft. The mathematical model of vertical shaft auxiliary ventilation is established to analyze the section of high concentration of gas in the tunnel. The simulation and analysis of the gas migration and distribution under the wind flow field are carried out, the general characteristics of the wind flow field and gas distribution under the auxiliary ventilation with a vertical shaft are obtained. The results provide reliable theoretical basis and technical support for gas accumulation prevention.

2. Gas Volume Calculation Method

The volume of gas emission from the gas tunnel is \( q \). Which is the sum of gas emission in the unclosed section \( q_1 \), the amount of gas in the closed section \( q_2 \) and the amount of gas emission from coal abandonment during excavation \( q_3 \) [13].

2.1. Gas Volume Discharged from the Unclosed Section

The amount of gas discharged from the newly exposed unclosed section during tunnel excavation can be calculated as follows:

\[
q_1 = A Q_0 f(t)
\]

(1)

where \( A \) is the newly exposed unsupported section area per day, \( m^2 \); \( Q_0 \) is the initial strength of gas per unit area; \( f(t) \) is the decay function of time.

2.2. Gas Volume Discharged from the Closed Section

During tunnel excavation, gas is infiltrated into the tunnel through tiny voids in the shotcrete or lining. The volume of gas infiltration is related to the gas content in the stratum, gas pressure, lining material, the permeability of the joint material, and the wind velocity in the tunnel. Therefore, the permeability coefficient method is commonly used to determine the amount of gas infiltration for gas tunnels.

\[
q_2 = \frac{kA(P_1^2 - P_2^2)}{2\gamma P_2} \times 10^5
\]

(2)

where \( k \) is the permeability coefficient of shotcrete or secondary lining, \( m/s \); \( P_1 \) is the gas pressure of the stratum after sealing, as shown in Table 1, MPa; \( P_2 \) is the air pressure in the tunnel; \( \gamma \) is the density of gas, \( kg/m^3 \); \( A \) is the air permeable area, \( m^2 \).

2.3. Gas Volume Discharged from Abandoned Rock during Excavation

The volume of gas discharged from abandoned rock during excavation can be calculated as:

\[
q_3 = V_a \rho W / 1440
\]

(3)

where \( V_a \) is the total volume of rock exploding daily, \( m^3 \); \( \rho \) is the density of rock, \( t/m^3 \); \( W \) is the gas volume discharged from per ton of rock, \( m^3/t \).
Table 1. The volume of gas permeation under different osmotic pressure

| Gas pressure (MPa) | Gas volume permeation in airtight concrete (m$^3$/s) | Gas volume permeation in ordinary concrete (m$^3$/s) |
|-------------------|-----------------------------------------------------|-----------------------------------------------------|
| 0.2               | 0.00020387                                          | 0.0020387                                           |
| 0.6               | 0.00237851                                          | 0.0237851                                           |
| 1.0               | 0.00672780                                          | 0.0672780                                           |
| 1.34              | 0.01213450                                          | 0.1213450                                           |

3. Mathematical Model of Gas Migration

3.1. Calculation Condition Setting

Under the ventilation condition of the gas tunnel in the stage of construction, the wind velocity of the outlet of the air duct and the jet fan is large, but the Mach number is still less than 0.3. Therefore, the compressibility of the air can be ignored [14]. For the air volume movement in the tunnel, it is generally considered that $Re≥10^5$, that is, the air volume is in the turbulent flow state. And the flow field in the tunnel is a three-dimensional, incompressible, viscous turbulent flow field.

The RNG $k$-$\varepsilon$ two-equation model was used to establish the calculated turbulence model. The general finite-rate model of the component model is used to simulate the coupling of gas and air in the tunnel. Mathematical models include continuity equations, momentum equations and $k$-$\varepsilon$ model equations, mass transport equations, and mass diffusion equations.

Turbulence intensity $I$ is a characteristic quantity of the relative intensity of the pulsating wind velocity in the reaction turbulence. When the wind velocity is higher than 0.25 m/s in tunnel, the inertial force plays a leading role, and the viscous force unable to overcome the disorder of the mass point and the fluid is in a completely turbulent motion state. The turbulence intensity of a fully developed tube flow core can be calculated as:

$$I = 0.16 (Re_D)^{-0.125}$$

In order to improve the accuracy of the calculation, the turbulent vortex should be considered. The turbulent scale $L$ is the physical quantity associated with the large eddy scale. In a fully developed tube flow, the calculated relationship between $L$ and the physical dimensions of the tube is as follows:

$$L = 0.07R$$

3.2. Boundary Conditions

In the air-gas migration model, the mesh of the excavation face and the tunnel wall is set as the gas source, and the boundary is set as the mass flow inlet. The tunnel entrance is set as pressure outlet and a relative pressure of 0Pa. The surface of the tunnel is set as wall, and the friction coefficient of the tunnel is 0.02, wall roughness constant $C_k = 0.6$, the thickness of the roughness $K_S = 0.03$. The air duct outlet is set as the velocity inlet. The surface roughness constant of the duct is 0.5, and the roughness thickness is 0.01. The vertical shaft exhaust outlet is set as mass outlet, the exhausted volume is slightly larger than the air duct supply, and the relative pressure at the exhaust is 0Pa.

4. Numerical Simulation Calculation Model

Numerical simulation model is established based on a 2-lane highway tunnel with vertical shaft auxiliary ventilation. The cross section area of the tunnel is 78.4 m$^2$, an axial fan is installed in the tunnel for local air supply, the diameter of the duct is 1.5 m, and the outlet of the duct is 15 m away from the excavation face of the tunnel. A vertical shaft is set for auxiliary ventilation, the diameter of which is 4 m. The calculation model is shown in Figure 1.
The relative volume of gas discharged in the tunnel is 2.58m³/t, the initial intensity of gas discharged is 0.039m³/(m²·min), and the initial gas pressure is 1.6MPa. The volume of gas emission from the coal seam wall is exposed to \( q_1 = 3.95 \text{m}^3/\text{min} \) per day. The gas emission from the wall of the shotcrete is \( q_2 = 1.93 \text{m}^3/\text{min} \). The volume of gas emission from the rock exposed by the excavation face is \( q_3 = 0.086 \text{m}^3/\text{min} \). The total volume of gas in the tunnel is \( q = q_1 + q_2 + q_3 = 5.966 \text{m}^3/\text{min} \).

According to the calculation result, the work area can be determined to be a gas tunnel of high concentration [15].

5. Characteristics of Flow Field in Tunnel

The Coal Mine Safety Regulations stipulates that the minimum allowable wind velocity in the excavation face and is 0.25m/s. The Technical Specification for Railway Gas Tunnels stipulates that the wind velocity in ventilation of gas tunnel construction should not be less than 1m/s [16]. In the actual project, the requirements of the specification cannot be met, the minimum wind velocity of the section is generally set as 0.5m/s with local auxiliary ventilation, due to the restrictions of ventilation equipment and ventilation length. In order to study the distribution characteristics of the flow field in the tunnel under different wind velocity, numerical simulation was conducted under the condition of different section average wind velocity, including 0.25m/s, 0.5m/s and 1.0m/s.

When the average wind velocity of cross section is 0.25m/s in the tunnel, the calculation results of the flow field in the tunnel are shown in Figure 2 and Figure 3. The fresh air is blown toward the excavation surface by the jet at the air outlet through the air duct, and the jet area is located near the tunnel vault, the excavation surface is within the area affected by the jet. The high-speed airflow is mixed with the surrounding air, and the jet section is enlarged. After reaching the excavation face, the flow is folded back, and the return airflow is distributed above the bottom surface of the tunnel. At 20m from the excavation face, the wind flow gradually reached a steady state, and the wind velocity is evenly distributed in the tunnel. At the location of vertical shaft, the gas flow into the vertical shaft and finally discharged through the vertical shaft. Under the conditions of 0.5m/s and 1.0m/s, there are the same distribution of wind velocity in the tunnel.
The air flow field at 2m above the tunnel ground is shown in Figure 4. At a wind velocity of 0.25m/s, there is a significant flow velocity pulsation near the duct outlet. The longitudinal wind speed pulsation value becomes smaller away from the excavation face, the fluid turbulence is weaken, and the airflow in the tunnel belongs to the unstable transition zone of the laminar flow to the turbulent transition. When the wind velocity of cross section is 0.5m/s, the wind velocity pulsation phenomenon is obvious, and the airflow in the tunnel enters the complete turbulence stage. When the wind speed of the tunnel section reached 1.0m/s, the wind speed pulsation phenomenon is further aggravated and the fluid turbulence is more severe.

It can be seen from the calculation that the airflow is in the laminar and turbulent transition phase under the condition of 0.25m/s, which is in the complete turbulent phase after the wind velocity is greater than 0.5m/s. Due to the laminar flow, gas and fresh air are not mixed closely, and gas stratification is prone to occur. Therefore, it is recommended that the wind velocity of the cross section in the tunnel should be 0.5 m/s at least during the construction stage.

6. Distribution of Gas Concentration in Tunnel
From the calculation results, it is known that there is a vortex zone between the excavation face and the air duct, and a large-scale eddy current is generated between the return air and the jet air. The fresh air is blown out by the air duct outlet and mixed with gas in the vortex area, the gas concentration near the face is higher than near the air outlet. With the distance from the excavation face increased, after passing through the vortex zone and the transition zone, the gas is blended evenly with the fresh air. The concentration of gas in the return air \((n)\) is the ratio of the absolute volume of gas generated \((q)\) to the fresh air volume \((Q)\). The gas concentration distribution is shown in Figure 5. Therefore, the
relationship between the required volume \(Q\) and the allowable of the maximum gas concentration \(n_1\) is \(Q = q/m_1\). Considering that the gas emission near the excavation surface is uneven, the same to the blending of fresh air and gas, and the imbalance coefficient \(K = 1.5 \sim 2.0\). At the same time, taking the inlet air volume \(n_2\) into consideration, the required air volume is \(Q = qK / (n_1 - n_2)\).

When the effective air volume of the excavation face is greater than the required air volume \(Q\) for the gas dilution, the gas concentration in the tunnel can be guaranteed to meet the requirements of gas controlling. Through numerical simulation analysis, when the effective air volume of the excavation face is greater than \(301\text{m}^3/\text{min}\), and the gas concentration in the tunnel can be diluted to the allowable concentration of 0.5% or less. The calculation of gas concentration longitudinal distribution in the tunnel under different wind velocity is shown in Figure 6.

![Figure 6. Distribution of methane in the tunnel](image)

(a) Wind velocity of 0.25m/s at the cross section
(b) Wind velocity of 0.5m/s at the cross section

It can also be seen from the calculation that when the wind speed is low, the buoyancy force caused by the decrease of the air density in the accumulation area will change the flow condition of the flow field. Which is obvious under the condition of 0.25m/s and 0.5m/s. According to the calculation results, there is gas backflow in some cases. A gas accumulation zone appears along the top of the tunnel, which usually appears near the excavation face and the vertical shaft. With the wind velocity increased, the gas accumulation area at the top decreases in the tunnel. When the wind velocity reached 1.0 m/s or even greater, the gas is completely diluted and there is no gas accumulation area at the top of the tunnel.

7. Conclusions
Three-dimensional numerical simulation was carried out to analyze the flow field and gas migration in gas tunnel with vertical shaft auxiliary ventilation, the following conclusions can be drawn:

1. The requirements of gas concentration dilution and cross-section wind velocity both must be met in tunnel. It should ensure that the airflow in the tunnel is completely turbulent, and gas stratification should be avoided through relevant measures. The cross-section wind velocity should be 0.5m/s at least. The effective air volume at the excavation for gas dilution to the allowable concentration should be not less than \(Q = qK / (n_1 - n_2)\).

2. Under the condition of auxiliary ventilation with a vertical shaft in tunnel, the methane zone is prone to accumulate at the top of the tunnel with 0.5~1.0m/s of cross-section wind velocity. Which is mainly concentrated near the excavation face and the vertical shaft, and local ventilation is required to dilute the gas. The gas can be diluted when the cross-section wind velocity is not less than 1.0m/s, and the conclusion can be used to the similar cases with a vertical shaft in tunnel.

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References
[1] Liu, D.W., Tang, Y., Li, B. (2015) Numerical simulation and test analysis of construction ventilation air duct optimization in gas tunnel. China Journal of Highway and Transport, 28: 98–142.
[2] Sasmito, A.P., Birgersson, E., Ly, H.C., Mujumdar, A.S. (2013) Some approaches to improve ventilation system in underground coal mines environment - A computational fluid dynamic study. Tunnelling and Underground Space Technology, 34: 82–95.
[3] Kurnia, J.C., Sasmito, A.P., Wong, W.Y., Mujumdar, A.S. (2014) Prediction and innovative control strategies for oxygen and hazardous gases from diesel emission in underground mines. Science of the Total Environment, 481: 317–334.
[4] Torno, S., Torano, J., Ulecia, M., Allende, C. (2013) Conventional and numerical models of blasting gas behaviour in auxiliary ventilation of mining headings. Tunnelling and Underground Space Technology, 34: 73–81.
[5] Keith, W., Brian, P., Daniel, S.J. (2015) The practice of mine ventilation engineering. International Journal of Mining Science and Technology, 25: 165–169.
[6] Ding, Y. (2011) Research on gas outburst mechanism and its early warning in highway tunnel. Chengdu University of Technology, Chengdu.
[7] Wu, Y.J., Yang, L.X., Gou, H.S. (2017) Analysis of influencing factors of gas outburst intensity of tunnelling face of gas tunnel and its control methods. Tunnel Construction, 37: 1262–1268.
[8] Zhang, X.L., Cai, J.H., Liao, Y.K. (2019) Characteristics analysis and forecast evaluation of gas occurrence of the Longquanshan tunnel on Chengdu metro. Modern Tunnelling Technology, 56: 25–30.
[9] Zeng, C., Yao, Z.G., Fan, Y. (2016) Study of gas distribution of highway tunnel using gallery ventilation. Tunnel Construction, 36: 837–843.
[10] Kang, X.B. (2011) Formation mechanism of gases in tunnels embedded in non-coal strata. Modern Tunnelling Technology, 48: 35–45.
[11] Zhang, C. (2018) Study on the gas emission law and its control measures in the shale section of highway tunnel. Chongqing University, Chongqing.
[12] Li, Y.S. (2018) Numerical study on gas distribution in non-rail transportation tunnel under construction. Railway Standard Design, 62: 97–107.
[13] Cao, W.Y. (2017) Construction ventilation optimization and risk management of large section gas tunnel. Chongqing University, Chongqing.
[14] Wang, Y.S. (2015) The influence of velocity of jet fan outlet on internal flow characteristic in tunnel. Anhui University of Science and Technology, Huainan.
[15] Gao, Y., Yang, C.Y., Zheng, W. (2017) Discussion on standards of classification of railway gas tunnel. Tunnel Construction, 37: 1366–1372.
[16] Kuang, L., Zhang, J.Y., Zhang, Z.Q. (2017) Research on the classification method of railway gas tunnel. Journal of Railway Engineering Society, 19: 73–77.