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Simulation Analysis of CO Concentration Distribution in Beijing Yuntong Tunnel

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Abstract

In this paper, the concentration distribution of CO emitted by motor vehicles in Beijing Yuntong Tunnel is simulated and analyzed based on Fluent numerical simulation software. Firstly, the physical model of tunnel geometry is established. Secondly, the suitable control equations and boundary conditions are selected to describe the diffusion distribution of pollutants in the tunnel. At the same time, the reliability of the model is verified according to the measured data, and the distribution law of CO concentration in the tunnel is observed through the simulation results. The tunnel is unorganized at the entrance of the tunnel. In the simulation results, the CO concentration at the entrance of the tunnel is far more than the CO unorganized emission limit in Beijing. The CO emission of the tunnel should be purified to prevent pollution of the urban environment.

Keywords

Numerical Analysis Method, Urban Tunnel, CO Emissions, Verification Analysis

1. Introduction

As a major engineering building to alleviate urban traffic pressure, urban tunnels are already very common in cities with high vehicle ownership. Beijing is the mega city. The urban tunnels are developing longer and larger. The Beijing Yuntong Tunnel is a one-way three lanes and length of 6310 m to become a representative of the city's long tunnels. Different from outdoor, the space in the tunnel is closed, and the pollutants are easy to accumulate. If the accumulated pollutants in the urban tunnel are discharged into the atmosphere without treatment, it will affect the surrounding environment of the tunnel entrance. The tunnel ventilation and air purification system can ensure the safety of driving and the health of the surrounding residents [1].

Simulation experiment, numerical analysis method and actual measurement method are the main methods to study the emission and diffusion of motor vehicle pollutants in tunnels [2]. The internal environment space of Yuntong Tunnel is large, and it is not easy to observe and analyze the distribution of internal pollutants by building an experimental platform. Simulation experiment method has become the best choice for research. Fluent is the most widely used computational fluid dynamics software. Cao studies the boundary conditions of indoor pollutant diffusion components through Fluent to determine that the boundary conditions of mass flow, component mass fraction and turbulence mode play a decisive role in the calculation results [3]. Based on Fluent, Liu Haoran simulated the pollutant diffusion concentration distribution in the office and obtained the distribution law of pollutants with air distribution [4]. In this paper, based on the Fluent software, the boundary condition constraints are applied to the tunnel model, and the distribution law of CO concentration in the tunnel under the disturbance of motor vehicle airflow is obtained.

The control of motor vehicle exhaust pollution in big cities is very important, which is particularly important for improving the effect of environmental protection, ensuring the health of urban residents and promoting social development [5]. Urban tunnels carry a large number of moving vehicles in the city. Studying the diffusion law of pollutants in tunnels is the key to preventing pollutants from escaping into the atmosphere. The state has become more stringent in the management of motor vehicle emissions while paying attention to the management of motor vehicle pollutant emissions in the tunnel, and the environmental protection effect in the city will be more significantly improved.

2. Basic Information of Tunnel

Beijing Yuntong Tunnel is located in the sub-center of Beijing and officially opened to traffic in January 2021. The tunnel passes under the whole line, the design speed is 80 km/h, the lane is two-way six lanes, and the outer lane is a large-capacity bus lane. The length of the closed section of the tunnel is 6310 m, the cross-sectional area of the tunnel is 82.3 m^2, the height of the tunnel is 6.8 m, the width of the tunnel is 12.25 m, the maximum slope of the road section is +3.5%, the longest section is 993 m, and the slope is +0.17%.

In July 2021, the research team carried out field measurement on the Yuntong tunnel. A total of three measuring points were set up. The layout positions were 1500 m, 3350 m and 4500 m from the entrance of the tunnel in the direction out of Beijing (right line). The measuring points were located at the ventilation of the tunnel distribution room, close to the wall surface, and about 1.5 - 3 m high; the measured contents include: traffic flow, traffic wind speed, CO concentration in the tunnel. During the measured period, the tunnel fan runs in different time periods, and the data is obtained when the fan is not running. **Figure 1** is the real picture of the tunnel. **Figure 2** is the layout of measuring points.

Figure 1. Tunnel photos.

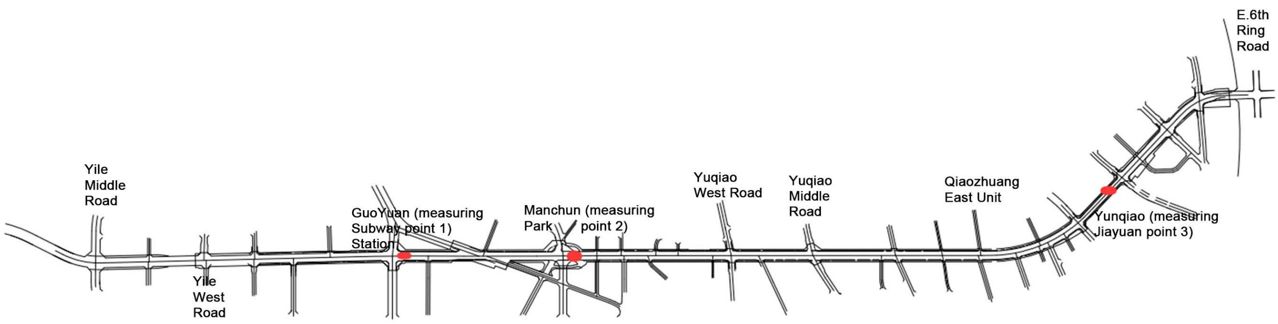


Figure 2. Measuring points in Yuntong tunnels.

3. Establishment of Tunnel Physical Model

The establishment of physical model is the basis of clear research object. The physical model can determine the spatial scope and geometric shape of the research, and the mathematical model can be established after the preliminary definition of the research object. The two models are mutually constrained and the appropriate numerical method is used to solve the research object more accurately. This section describes the process of establishing the physical model of Yuntong tunnel. Through reasonable simplification, analysis and summary of model establishment ideas, combined with model establishment ideas and engineering drawings, the physical model of the tunnel is established, and the physical model is meshed by software.

3.1. Model Building Clue

In order to ensure the accuracy of the simulation results, through reasonable simplification and analysis, the setting method of model boundary conditions is determined. The specific simplification of the model and the setting of boundary conditions are as follows:

① The Beijing Yuntong Tunnel was officially opened to traffic in January 2021. The measured period belongs to the trial operation stage of the tunnel, with fewer motor vehicles. The measured data is set as the boundary condition of the simulation model;

② The distribution of CO concentration is used to represent the distribution of pollutant concentration in the tunnel;

③ The distance between the vehicle exhaust pipe and the ground is compared with the height of the tunnel. It can be assumed that the vehicle exhaust pipe is close to the ground of the road. When the model is established, the vehicle in the tunnel is simplified into a flat plate to release the pollution source in the closed space;

④ Without considering chemical reaction.

3.2. Physical Model Establishment

In this paper, the 1:1 geometric model of Beijing Yuntong Tunnel is established by using Rhino3D drawing software. When establishing the model, the decoration of the inner wall of the tunnel is neglected and the smaller slope is neglected. The tunnel is simplified as a hexagon with a total length of 6310 m, a section of 12.25 m at the bottom, 10.12 at the bottom, and a height of 6.8 m. The simulation calculation focuses on the diffusion of pollutants.

3.3. Mesh Subdivision

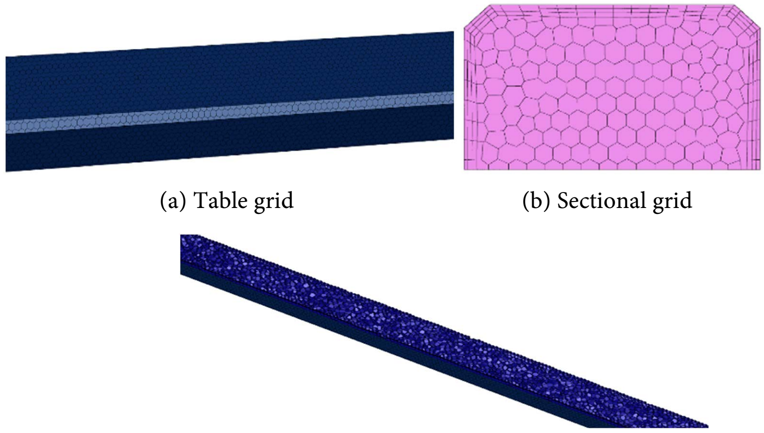
In this study, Fluent Mashing meshing software was used. Because the tunnel was long and the cross-sectional area was small, the pollution source was simplified to an outer-swept plate for pollutant diffusion calculation. In order to simplify the calculation time and ensure the accuracy of the calculation, the hexahedral unstructured grid was used to mesh the model to reduce the number of model nodes. At the same time, according to the third item in the modeling idea, the vehicle pollution source discharge port is merged with the lower surface of the model, and the lower surface area is too large without mesh encryption. Figure 3 is the grid division diagram of tunnel physical model.

4. Method of Calculation

In this paper, computational fluid dynamics technology is used to study the distribution of pollutant concentration in the tunnel, and the calculation results are verified by experimental fluid mechanics. The research of computational fluid dynamics usually follows the following steps: first, determine the geometric description of the flow region, including the geometric shape of the flow field, the flow conditions and the requirements of numerical simulation; secondly, the control equations and boundary conditions are selected. Then determine the meshing strategy and numerical method; then the corresponding CFD software is used to solve the fluid dynamics equation and obtain the numerical solution. Finally, the numerical solution is post-processed to display and analyze the flow field.

4.1. Mathematical Method

In this paper, Fluent 2020 is used to calculate the wind speed field and pollutant



(a) Table grid (b) Sectional grid

(c) Volume grid

Figure 3. Grid division diagram.

concentration distribution in the tunnel. Determining the research problem is the first step in fluid mechanics calculation, including the determination of flow field geometry, flow conditions and numerical simulation boundary conditions. Secondly, the suitable control equations and boundary conditions are selected to describe the pollutant diffusion distribution in the tunnel model. The N-S equation can describe the movement of Newtonian fluid. The N-S equation includes mass conservation equation, momentum conservation equation and energy conservation equation.

Considering that the fluid flow inside the tunnel is mainly the turbulent flow of ideal fluid, and this paper mainly studies the distribution of pollutant concentration. The most widely used turbulence model is selected to describe the turbulent flow of pollutants in the tunnel. The standard K-ε two-equation is used as the control equation of the gas flow state in the tunnel. The advantage is that the standard K-ε model has strong adaptability to the velocity field. The pressure-velocity coupling SIMPLEC algorithm is used to accelerate the convergence.

a) Law of conservation of mass

The integral type is:

$$\frac{\partial}{\partial_t}\iiint\limits_{\Omega}\rho \mathrm{d}\Omega + \oiint\limits_{s}\rho V\cdot n\mathrm{d}S = 0$$

where Ω is the control of the integral equation, $\mathrm{d}\Omega = \mathrm{d}x\mathrm{d}y\mathrm{d}z$, $S = \partial\Omega$ is the surface of the control body, ρ is the density, and V is the velocity vector of the fluid motion.

The differential equation is:

$$\frac{\partial\rho}{\partial_t} + \nabla\cdot\rho V = 0$$

b) Law of conservation of momentum

The integral type is:

$$\frac{\partial}{\partial_t}\iiint_{\Omega}\rho V \mathrm{d}\Omega + \oiint_{s}\rho VV\cdot n\mathrm{d}S = \iiint_{\Omega}\rho F\mathrm{d}\Omega + \oiint_{s}\rho\left(-P\overline{I}+\overline{\overline{\zeta}}\right)\cdot n\mathrm{d}S$$

The differential equation is:

$$\frac{\partial(\rho V)}{\partial_t}+\nabla\cdot\rho V=\rho F+\nabla\cdot\left(-P\overline{I}+\overline{\overline{\zeta}}\right)$$

where $\overline{I}$ is the unit tensor, p is the pressure, and $\overline{\overline{\zeta}}$ is the viscous stress tensor.

c) Law of conservation of energy

When there is no heat source in the flow field, the integral energy conservation equation is:

$$\frac{\partial}{\partial_t}\iiint_{\Omega}\rho E\mathrm{d}\Omega + \oiint_{s}\rho EV\cdot n\mathrm{d}S = \iiint_{\Omega}\rho FV\mathrm{d}\Omega + \oiint_{s}\left[\left(-P\overline{I}+\overline{\overline{\zeta}}\right)\cdot V-q\right]\cdot n\mathrm{d}S$$

The differential equation is:

$$\frac{\partial(\rho E)}{\partial_t}+\nabla\cdot\rho EV=\rho F\cdot V-\nabla\cdot q+\nabla\cdot\left(-P\overline{I}+\overline{\overline{\zeta}}\right)\cdot V$$

where E is the total energy and q is the heat flux.

d) K-ε model:

K-ε is the most widely used turbulence model. The standard K-ε model used in this study has wide adaptability to conventional velocity field and heat transfer model.

The K equation is:

$$\frac{\partial(\rho k)}{\partial_t}+\frac{\partial(\rho k\mu_i)}{\partial_{xj}}=\frac{\partial}{\partial_{xj}}\left[\left(\mu+\frac{\mu_i}{\sigma_k}\right)\frac{\partial k}{\partial_{xj}}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_K$$

The ε equation is:

$$\frac{\partial(\rho\varepsilon)}{\partial_t}+\frac{\partial(\rho\varepsilon\mu_i)}{\partial_x}=\frac{\partial}{\partial_{xj}}\left[\left(\mu+\frac{\mu_i}{\sigma_k}\right)\frac{\partial\varepsilon}{\partial_{xj}}\right]+C_{1e}\frac{\varepsilon}{k}\left(G_k+G_{3e}G_b\right)-C_{2e}\rho\frac{\varepsilon^2}{k}+S_K$$

where G_k represents the turbulent kinetic energy generated by the laminar velocity gradient; G_b is the turbulent kinetic energy generated by buoyancy; C_{1e}, C_{2e}, C_{3e} are constants.

4.2. Mathematical Method

The boundary condition of the pollution source is set to the velocity inlet boundary condition, so the pollutant emission rate represented by the mass flow rate needs to be converted into velocity for calculation.

PIARC 2019 [6] gives the calculation formula of vehicle pollutant emissions. Because the vehicle type in the tunnel is single, the formula is simplified according to the actual road conditions to obtain Equation (1).

$$Q = q_{ex}(v,i) \cdot f_h \cdot f_t \cdot f_e \tag{1}$$

In the formula, Q is the single vehicle emissions of CO and NOx, g/(h); $q_{ex}(v,i)$ is the single vehicle emission factor of CO of PC in Class A area, which is related to vehicle speed and road slope. The vehicle speed of the control model is 50 km/h, g/(h); f_h is the altitude correction coefficient, 1 in Beijing; f_t is the annual correction coefficient, and the CO correction coefficient in 2020 is 0.91. f_e is the influencing factor of other technical standards, and 1 is taken for the calculation of yuntong tunnel.

The results obtained from the PIARC2019 version are the mass flow results. Through the mass fraction of each pollutant component in the automobile exhaust, the exhaust emission rate of a single car under the blocking condition is calculated.

The number of vehicles in the tunnel is calculated by Equation (2), and taking into Equation (1) to calculate the total emission rate of all motor vehicles in the tunnel.

$$n = \frac{N \times L \times 0.001}{v} \tag{2}$$

In the formula, N is traffic flow, veh/h; L is tunnel length, m; v is the speed, km/h.

The total vehicle exhaust emission rate formula is as follows:

$$Q = M_{\text{exhaust emission}} \times n \tag{3}$$

Because the Velocity-inlet boundary condition is assigned to velocity, not mass flow. Therefore, it is necessary to convert it into volume flow rate, and then obtain the corresponding exhaust outlet speed, from formula (4)-(6).

$$\rho = \frac{M}{V} = \frac{M_{O_2,CO_2,CO,H_2O,N_2}}{\rho'_{O_2,CO_2,CO,H_2O,N_2}} \tag{4}$$

$$G = \frac{Q}{\rho} \tag{5}$$

$$v' = \frac{G}{\rho \times A} = \frac{Q}{\rho \times \rho \times n} \tag{6}$$

where, ρ is the density of pollutants, and the exhaust density of single vehicle is 1.23 kg/m^3; V is the total volume of exhaust gas, m^3; M is the mass of each component, O_2 = 0.0224, CO_2 = 0.1689, CO = 0.0049, H_2O = 0.0754, N_2 = 0.7284; the density of each component is O_2 = 1.429 kg/m^3, CO_2 = 1.977 kg/m^3, CO = 1.25 kg/m^3, H_2O = 0.6 kg/m^3, N_2 = 1.25 kg/m^3. G is the volume flow, m^3/s; v', is the exhaust outlet velocity, m/s; A is the area of pollutant emission source.

5. Results Analysis

In this study, the model volume is large, the ideal grid size is small and the calculation result is accurate. Affected by the actual conditions, the larger the grid density and the more grids, the longer the calculation time. Therefore, this simulation study simplifies the grid into a hexahedral unstructured grid, with a total of 1.2 million grids.

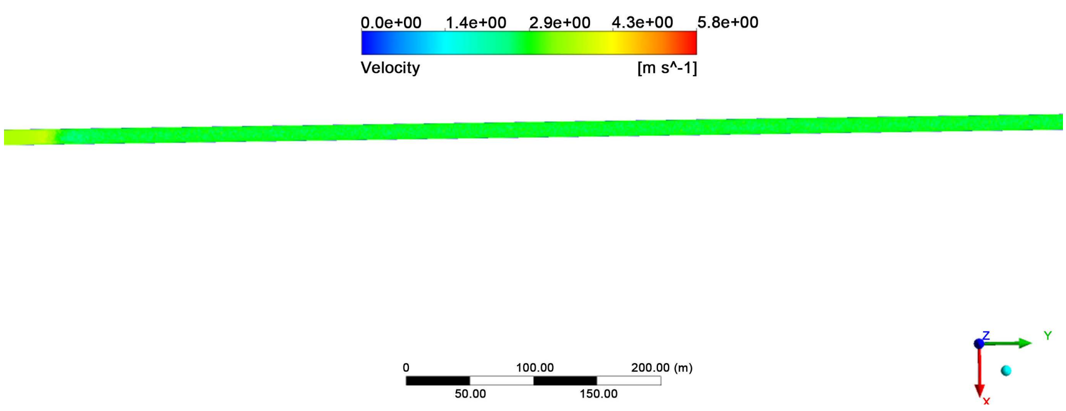
The tunnel entrance and exit are set as the velocity inlet boundary condition. According to the measured data, the average wind speed is 3.6 m/s when there are few vehicles in the tunnel. Therefore, the tunnel entrance boundary condition is set to $V = 3.6$ m/s, and the airflow direction is the driving direction. The tunnel outlet boundary is set as the pressure outlet to suppress the backflow, and the tunnel wall is set as the adiabatic and fixed wall boundary conditions. The measured tunnel traffic flow is 1400 veh/h. The lower surface of the model is used as the emission source, and the emission direction is positive in the Z axis. According to Chapter 3.2, the tunnel pollutant emission rate can be calculated to be 1.037×10^{-6} m/s.

The above simulation results are all natural conditions. The mechanical ventilation system inside the tunnel is all closed. The CO distribution map at 2 m height in the tunnel is shown in **Figure 4(b)**. It can be seen from the CO distribution cloud map that under the action of traffic wind and natural wind, the CO concentration is proportional to the distance from the hole, and CO accumulates along the direction of motor vehicle driving, up to 10.8 ppm. Combined with the analysis of the vector diagram of the wind speed field in **Figure 4(a)**, it is found that due to the piston wind in the tunnel, the fresh air outside the tunnel will dilute the pollutant concentration in the tunnel and reduce the CO concentration at the entrance of the tunnel.

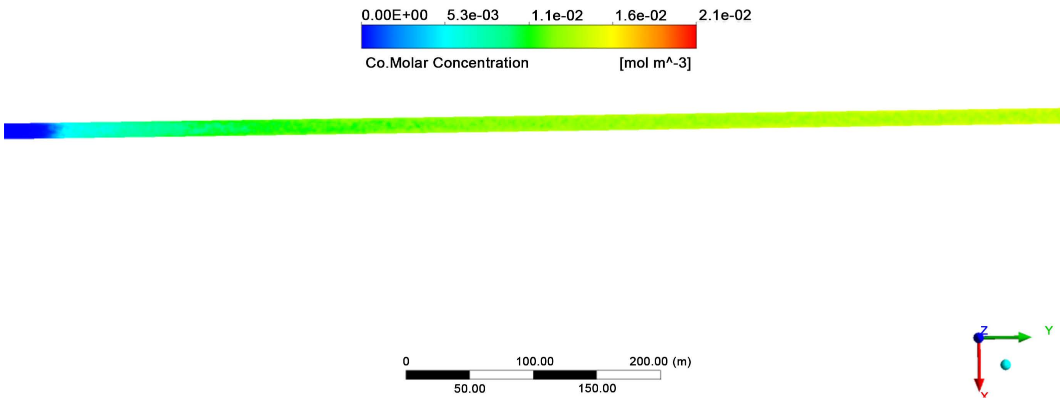
From the longitudinal profile of **Figure 5**, it can be seen that the CO concentration diffuses upward and distributes uniformly, which is the same as the theoretical study. Therefore, it can be concluded that the calculation of this model is reliable. Based on the calculation results, the CO distribution of Yuntong Tunnel can be preliminarily analyzed.

6. Conclusions

1) Yuntong tunnel is located in the sub center of Beijing city, special geographical location in the tunnel construction without ventilation shaft emissions

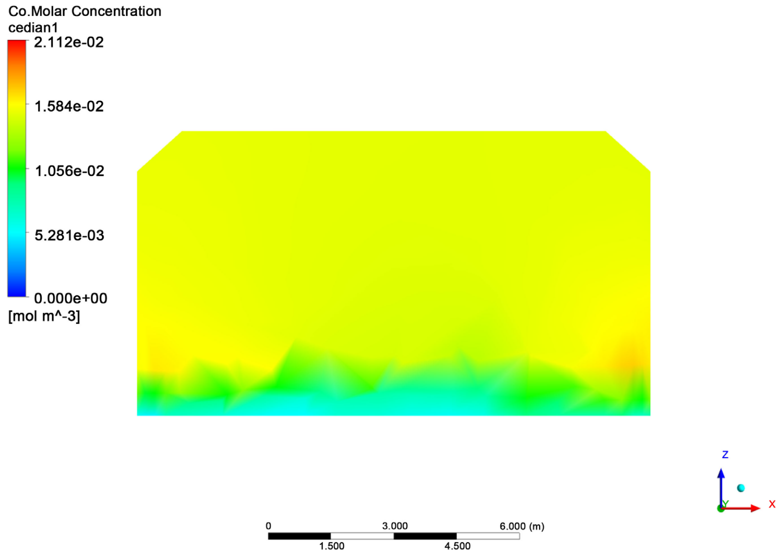


(a) Wind speed cloud

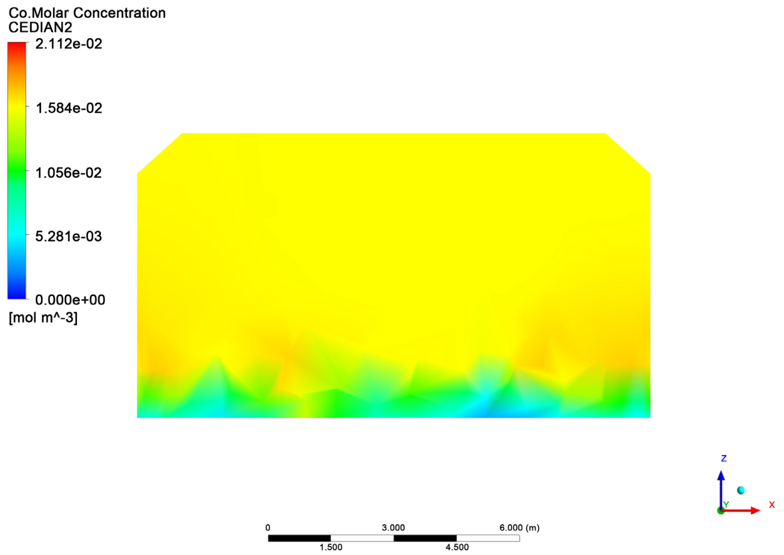


(b) Concentration cloud diagram

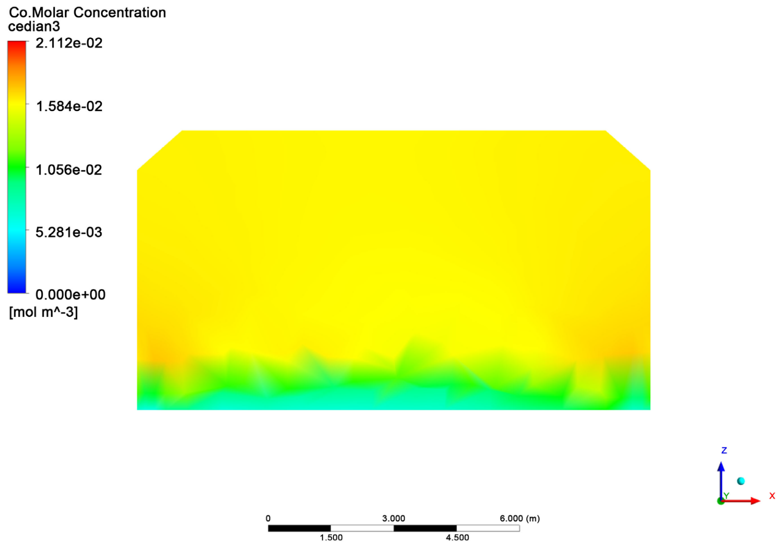
Figure 4. From the ground 2 m overlook profile cloud.



(a) Measuring point 1



(b) Measuring point 2



(c) Measuring point 3

Figure 5. CO concentration distribution profile of measuring point.

Table 1. Comparison of simulation results and measured results.

Measuring point	wind velocity (m/s)		relative error	co concentration (mg/m^3)		relative error
	measured value	value of simulation		measured value	value of simulation	
Measuring point 1	1.88	1.92	2.23%	5.36	5.84	8.09%
Measuring point 2	1.94	2.18	10.97%	7.45	8.43	11.59%
Measuring point 3	2.20	1.90	13.51%	8.38	9.98	16.09%

of pollutants, only through the tunnel exit for fugitive emissions, according to the simulation calculation of tunnel exit CO concentration value reached 12 mg/m^3, far more than the Beijing fugitive emissions limit, need to open the purification device in the tunnel exit.

2) The 'Highway Tunnel Ventilation Design Rules' 2014 edition [7] stipulates that the design concentration of CO in long tunnels greater than 3000 m is less than 100 mg/m^3, and the design concentration of CO in PIARC2019 is less than 70 ppm ≈ 87.5 mg/m^3. In the simulation results, the CO concentration in the tunnel is lower than the design concentration, and the number of fans can be appropriately adjusted to save energy.

3) By comparing the measured data and simulation data to verify the reliability of the model established in this paper, the model can be used to predict the CO concentration of the tunnel or to simulate the diffusion of NOx, another major pollutant of motor vehicles (**Table 1**). Table type styles (table caption is indispensable).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Wang, P. and Yang, J.N. (2021) Urban Tunnel Operation Ventilation and Purification System Design. *Modern Transportation Technology*, **18**, 71-76.

[2] Deng, S.X. (2004) Analysis Method of Air Pollution Impact on Highway and Long Tunnel. Science Press, Beijing.

[3] Cao, Y.P. (2021) Study on the Boundary Conditions of Indoor Pollutant Diffusion Components by FLUENT Numerical Simulation. *Energy and Energy Conservation*, 104-105+127.

[4] Liu, H.R., Wei, X.D. and Cedar, U. (2019) Simulation Calculation of Pollutant Diffusion Concentration Distribution in Office Based on FLUENT. *Journal of Jilin Jianzhu University*, **36**, 48-52.

[5] Zhang, F.L. (2021) Study on the Prevention and Control Measures of Motor Vehicle Exhaust Pollution in Big Cities. *Leather Production and Environmental Protection Technology*, **2**, 112-113.

[6] PIARC-World Road Association (2019) Road Tunnels: Vehicle Emissions and Air Demand for Ventilation. France.

[7] Ministry of Transport of the People's Republic of China (2014) Technical Standards for Highway Engineering: JTG B01-2014. People's Transportation Publishing House, Beijing.