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Numerical Investigation of Polluting Gas Diffusion Outside Tunnel Portal at Low Wind Speed

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Abstract: Diffusion of polluting gas outside urban tunnel portal has always been closely watched. In order to study the influence of polluting gas, a tunnel in Chongqing is set as an example, which is based on the diffusion theorem. In this paper, it's used COMSOL Multiphysic software to establish a three-dimensional model which simulates the diffusion of polluting gas outside tunnel portal at low wind speed. The simulation result shows that the influence of gas diffusion along the tunnel axis direction is greater than that to the both sides of road and upper side. Along the tunnel axis direction, it's about 250m away from the tunnel portal that the concentration of CO decays to the specification requirements. However, to the both sides of road and upper side, it's about 30m that the concentration of CO has decayed to the specification requirements.

Key words: Gas diffusion; numerical simulation; concentration distribution

INTRODUCTION

The urban tunnel is a relatively closed space, only the import and export are interlinked to atmosphere. In the operating environment, the vehicles of the urban tunnel emit a large amount of harmful gas (Kuang *et al*., 2006; Wang *et al*., 2010). The waste gas is concentrated discharged from the tunnel portal, leading to the pollutants concentration outside the tunnel portal is too high. Therefore, it's extremely important to study the diffusion of polluting gas outside urban tunnel portal.

It is in the 1970's, researchers abroad had begun to study the diffusion of polluting gas outside tunnel portal. While Chinese researchers started relatively late, in the 1980's. For decades, scholars at home and abroad have made a great contribution. Hayward and Macdonald (1973) had made model tests to study the pollution problem of the tunnel portal. Ide *et al*. (1987) and Nadel *et al*. (1994) had made simulation experiments in Rowan Williams and Irwin laboratory, Ontario, Canada. Integrating a variety of factors, they concluded the basic mechanism about the diffusion of polluting gas in the tunnel portal. Brousse *et al*. (2005) had established a model which simulates the surroundings of St. Denis station in France with 1:140 ratios for wind tunnel tests. They had measured the data of transient changes in pollutant concentration. Considering various factors (Matsumoto *et al*., 1998) compiled modules that adapted to simulate different situations. Yu and Jiang (1996) of Nanjing University had conducted ventilation model test and numerical simulation for river-crossing tunnel. Comparing the results they obtain the distribution of the diffusion flow field. Jiang *et al*. (1998) and Hu (1997) had established a 1:500 scale model which based on the size and the surrounding geographical features of the tunnel portal in Yan Dong Road, Shanghai and tested in Nanjing University's experiment. Deng *et al*. (2006), Yang and Kuang (2004), Kuang *et al*. (2005) and Yu *et al*. (2005) had respectively conducted numerical simulation on pollutants diffusion outside the tunnel portal.

Many articles select such model that the urban tunnel entrance is below ground. While some urban tunnel entrance in Chongqing is above ground. In this paper, we establish the model that tunnel entrance is above ground and conduct numerical simulation based on COMSOL. In the case of the wind speed outside tunnel portal is low, due to the effect of the jet fan inside the tunnel the polluting gas discharged from tunnel portal diffuses along tunnel axis faster than that to the both sides of road and the sky.

MODEL OF POLLUTING GAS DIFFUSING OUTSIDE TUNNEL PORTAL

Basic assumptions: The composition of polluting gas in tunnel is diversity and the movement of polluting gas complex. Generally, the fluid has viscosity and compressibility. Therefore, in order to facilitate the

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researching, the polluting gas flowing at tunnel portal can be simplified and the assumptions can be made to the gas as followed (Kuang *et al*., 2006):

- Ignoring other diffusion mechanism and considering only the diffusion caused by the jet
- The fluid is steady flow, with incompressibility
- Ignoring other components of polluting gas and considering only the CO
- Within a short time, the external environment, such as air flow and temperature, is relatively stable
- In the tunnel exit section, the velocity and concentration are uniformly distributed

The basic theory of fluid diffusion: The Fick's first law: In unit time, the amount of substance that through unit cross-sectional area is proportional to the concentration gradient of the section. The mathematical equation can be represented as follows:

$$N = -D_m \frac{\partial c}{\partial x} \tag{1}$$

where, N is diffusion flux of the diffusion material along the spreading direction kg/(m^2 sec^{-1}); c is concentration of the diffusion material, kg m^{-3}; D_m is diffusion coefficient, m^2 s^{-1}.

The Fick's second law reflects the changing of concentration along with time. For the diffusion in fluid is isotropic diffusion, the mathematical equation can be represented as follows:

$$\frac{\partial c}{\partial t} = D_m \left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right) \tag{2}$$

Convection diffusion equation is the basic equation that characterizes the mass transfer regularities of flow system, the mathematical equation can be represented as follows:

$$\frac{\partial c}{\partial t} + u_j \frac{\partial c}{\partial x_j} = D_m \frac{\partial^2 c}{\partial x_j^2} + r \tag{3}$$

where, r represents chemical reaction.

As assuming that air flow is steady or change smaller, the car exhaust emissions continuously and pollutants is stable in distribution. So the concentration of the pollutants in a certain time does not change with time and the D_m and u are constant. The equation can be simplified as:

$$u_j \frac{\partial c}{\partial x_j} = D_m \frac{\partial^2 c}{\partial x_j^2} + r \tag{4}$$

NUMERICAL SIMULATION OF POLLUTING GAS DIFFUSION OUTSIDE TUNNEL PORTAL

The selection of calculation model: The computational domain is cubic area which is outside the tunnel portal. The length, width and height of the model are 270, 100 and 50 m. The tunnel portal is above the horizon and the tunnel portal is simplified to a small cuboid which volume is 20×10×6 m. Polluting gas is discharged from the small rectangular section which area is 10×6 m. The model is shown in Fig. 1.

Boundary conditions: According to Specifications for Design of Ventilation and Lighting of Highway Tunnel (Industry Standard of the People's Republic of China, 1999), airflow velocity in the one-way traffic shall not exceed 10 m sec^{-1} and the airflow velocity in two-way traffic tunnel shall not exceed 8 m sec^{-1}. As the tunnel length is less than 1000 m, the highest concentrations of CO must not exceed 250 ppm. In order to ensure safety, assuming that the speed of polluting gas discharged from tunnel portal is 5 m sec^{-1} and the concentration of CO is 100 ppm, about 4.0×10^{-3} mol m^{-3}.

Simulation parameters: The diffusion coefficient of polluting gas is 1.92×10^{-5} m^2 sec^{-1}. Outside the tunnel portal, we treat the far-field pressure as standard atmospheric pressure. The wind speed is low, about 1 m sec^{-1} and the wind direction is along the tunnel axis.

Simulation results and analysis: This three-dimensional model is simulated in the convection and diffusion module of the COMSOL software. The diffusion situation of the polluting gas discharged from tunnel portal is shown in Fig. 2.

Figure 2a is concentration isosurface. The CO concentration of the outermost layer is 1.3334×10^{-4} mol m^{-3}, while the innermost layer is

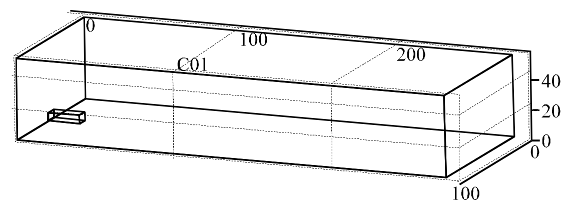

Fig. 1: Model of the simulated space

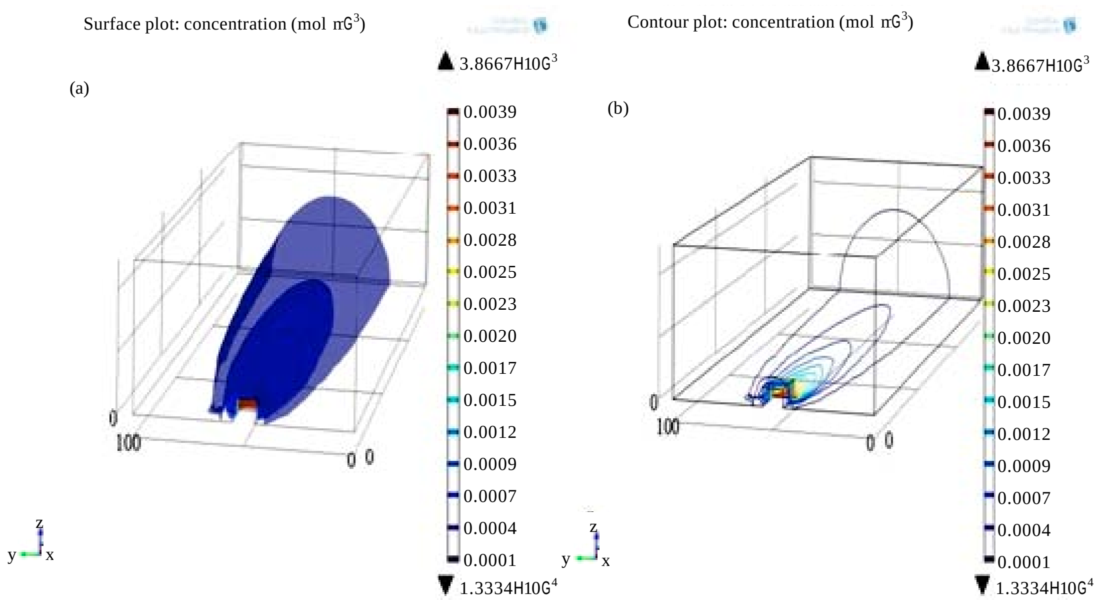

Fig. 2(a-b): The situation of concentration distribution, (a) Surface plot of concentration and (b) Contour plot of concentration

3.8667×10^{-3} mol m^{-3}. The concentration difference between two adjacent isosurfaces is about 3×10^{-4} mol m^{-3}. Figure 2b is concentration contours.

According to Ambient Air Quality Standard (Industry Standard of the People's Republic of China, 2012), the CO concentration limit is that the short-term concentration is 10 mg m^{-3} and the daily average concentration is 4 mg m^{-3}. That is to say that in a long time, the CO concentration shouldn't be more than 4 mg m^{-3} (about 1.4×10^{-4} mol m^{-3}), however, in a short time, the CO concentration can be more than 4 mg m^{-3} but not be more than 10 mg m^{-3} (about 3.57×10^{-4} mol m^{-3}). In Fig. 2, the lowest concentration of CO is less than the daily average concentration limit.

In order to illustrate the diffusion of CO, we intercept two-dimensional plane from the entire computational domain and the concentration distribution of CO in different sections will be showed.

In Fig. 3, it is shown that the concentration distribution of CO on different X-Y sections with different height from the ground. In Fig. 4, it is shown that the concentration distribution of CO on different X-Z sections with different distance from the tunnel axis (in the tunnel axis, Y = 50 m).

Figure 3a is the section with height of 1.5 m (Z = 1.5 m), the height of this plane is the height of respiration. Therefore, it's more meaningful to take this plane as research object than the ground. From the figure, it can be concluded that the concentration of CO decays gradually as the increase of distance from tunnel portal and the decay rate gradually slow. Within 80 m away from the tunnel portal, the concentration of CO decays from 3.87×10^{-3} mol m^{-3} to 1.2×10^{-3} mol m^{-3}, while from 80 m to the control border, the concentration of CO decays from 1.2×10^{-3} mol m^{-3} to 1.33×10^{-4} mol m^{-3}. In this section, about 250 m away from the tunnel portal, the concentration of CO is reduced to the concentration allowed. The heights of Fig. 3b-d are respectively 10, 20 and 30 m. In Fig. 3b-c, the concentration of minimum concentration contours are set as 1.4×10^{-4} mol m^{-3} to distinguish contaminated and non-contaminated areas. While in Fig. 3d, for the concentration of CO in this section is close to the standard value, the concentration of maximum concentration contour is set as 1.4×10^{-4} mol m^{-3}. The four pictures of Fig. 3 show that the CO diffusing along X axis direction is faster than that along the Z axis direction. It can be concluded that the concentration of CO will up to standard at the altitude of 30 m.

Figure 4a shows the concentration contours of the vertical section which along tunnel axis (Y = 50 m, the X-Z section). The concentration in this section is highest among the four sections. Figure 4b-d are respectively the concentration contours in X-Z sections of Y = 40 m, Y = 30 m and Y = 20 m. In Fig. 4b and c, the concentration of minimum concentration contours are also set as

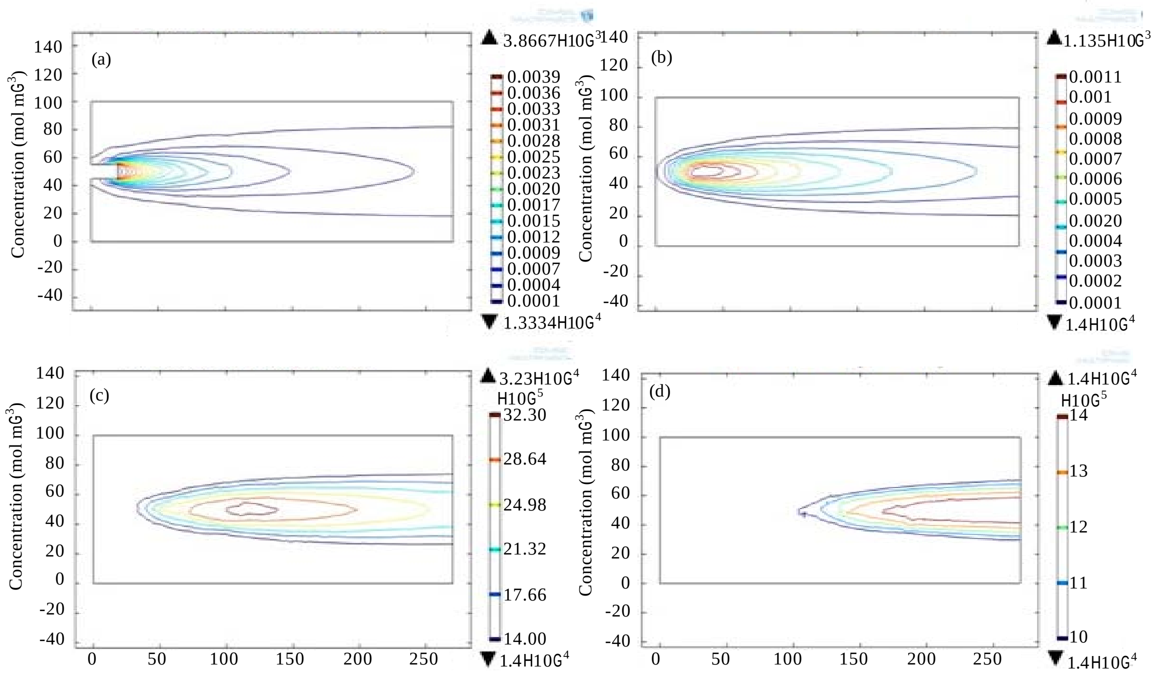

Fig. 3(a-d):Concentration distribution of CO at different X-Y planes, (a) z = 1.5 m, (b) z = 10 m, (c) z = 20 m and (d) z = 30 m

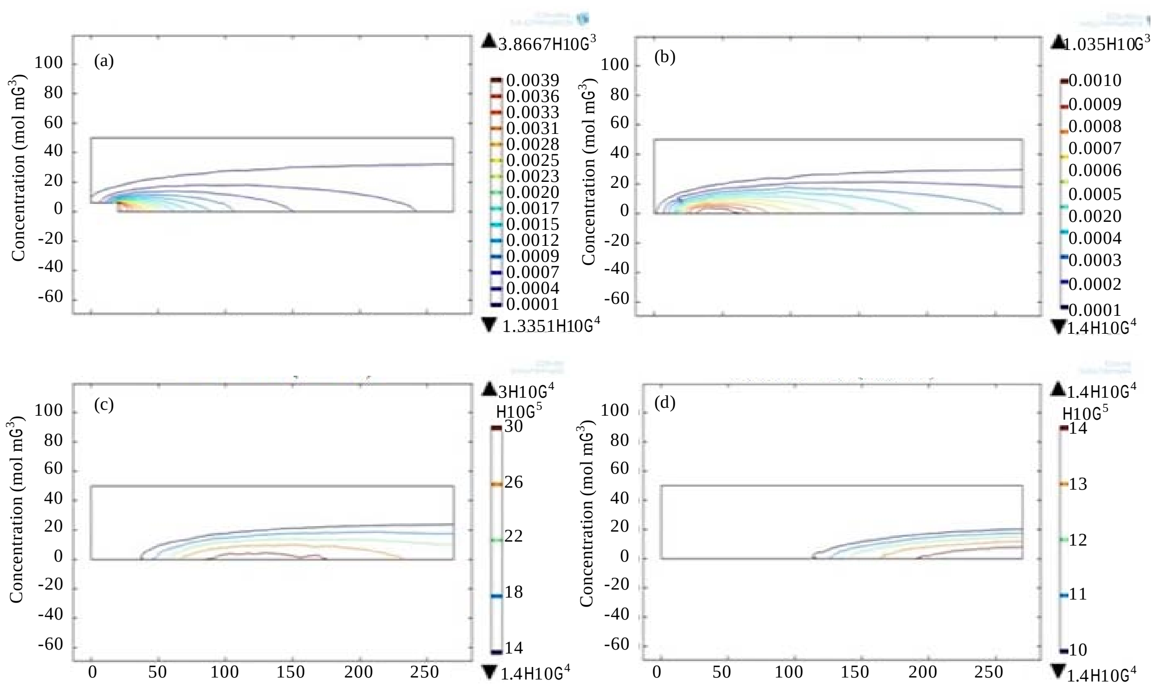

Fig. 4(a-d): Concentration distribution of CO at different X-Z planes, (a) y = 50 m, (b) y = 40 m, (c) y = 30 m and (d) y = 20 m

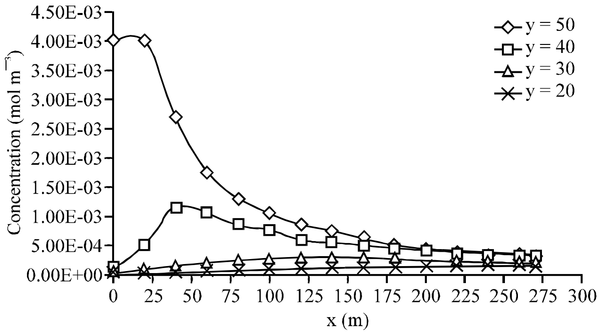

Fig. 5: Concentration graph of CO in different X-Z sections at height of 1.5 m (Z = 1.5 m)

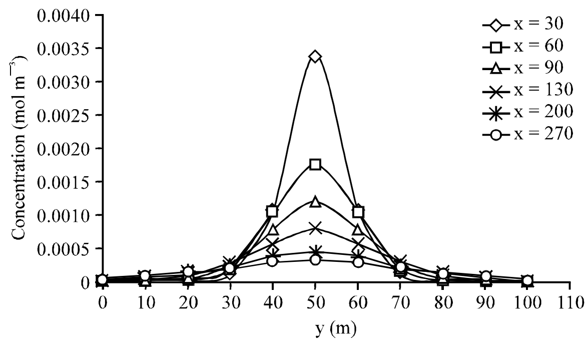

Fig. 6: Concentration graph of CO in different Y-Z sections at height of 1.5 m (Z = 1.5 m)

1.4×10^{-4} mol m^{-3} to distinguish contaminated and non-contaminated areas. In Fig. 4d, the concentration of maximum concentration contour is set as 1.4×10^{-4} mol m^{-3}. It can be concluded from Fig. 4 that the concentration of CO will up to standard in the vertical section which is 30 m away from the tunnel axis.

Most of the urban tunnels are in the centre of city blocks where is surrounded by high buildings and people passing frequently. Therefore, CO discharged from tunnel portal diffusing to both sides of road affects surroundings greatly. And it's extremely important to research the distribution of concentration. The Fig. 5 below will illustrate the concentration difference in Fig. 4.

The graph shown in Fig. 5 is comparison of CO concentration distribution in different X-Z sections at the height of 1.5 m (Y = 50, Y = 40, Y = 30 and Y = 20). As is shown in the figure, within 150m away from the tunnel portal, there is a big gap in concentration of different sections. While from 150 to 270 m, the concentration of different sections are closed to each other. In the vertical section of Y = 50 m, the concentration of CO is highest but it has little influence on people for there is no people passing by. In the vertical section of Y = 40 m, it is about 40 m away from the tunnel portal that the concentration of CO is highest, up to 1.2×10^{-3} mol m^{-3}. About 200 m away from the tunnel portal, the CO concentration reduces to 3.6×10^{-4} mol m^{-3} which can basically meet the specification 10 mg m^{-3} (about 3.57×10^{-4} mol m^{-3}). In the section of Y = 30 m, the concentration of CO can also meet the specification of 10 mg m^{-3}. However, in the section of Y = 20 m, the concentration of CO can meet the specification of 4 mg m^{-3} (about 1.4×10^{-4} mol m^{-3}).

The graph shown in Fig. 6 is comparison of CO concentration distribution in different Y-Z sections at the height of 1.5 m. It is concluded from the figure that about 200 m away from the tunnel portal, the highest concentration of CO approximately is 10 mg m^{-3} (about 3.57×10^{-4} mol m^{-3}). However, about 270 m away from tunnel portal, the highest concentration of CO approximately is 4 mg m^{-3} (about 1.4×10^{-4} mol m^{-3}).

As the urban tunnels are in special position, there always are surrounded by high-rise buildings within 20 m away from both sides of the tunnel portal. In the case of wind speed is low and the wind direction is along the tunnel axis, the polluting gas discharged from tunnel portal will affect this area.

CONCLUSION

Compared to FLUENT, the COMSOL has the limitations in applying to the fluid. Therefore, in this paper, external factors are ignored and the flow field is simplified when using COMSOL software to simulate the polluting gas diffusion. In the case of the wind speed is low and the wind direction is along the tunnel axis, the polluting gas discharged from tunnel portal diffuses along tunnel axis faster than that to the both sides of road and the sky. About 250 m away from tunnel portal, the concentration of CO can meet the specification that the daily average concentration should not be more than 4 mg m^{-3} (about 1.4×10^{-4} mol m^{-3}). While about 30 m away from tunnel axis and 30 m high from ground, the concentration of CO has met the specification.

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