Numerical Simulation of Effects of Ventilation and Vehicle Speeds on CO Distribution in Tunnel

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Abstract: In this paper, 2D models were established for the tunnel horizontal section to simulate the CO distribution in tunnel, and the effect of ventilation and vehicle speeds on CO distribution were analyzed. Results show that both ventilation speed and vehicle speed affect CO distribution in the tunnel. CO mostly distributes in the central area located 20m behind the last vehicle, and CO concentration in this area increases with the increasing ventilation speed but decreases with the increasing vehicle speed. In the side areas of tunnel, CO concentrations are far lower than in the central area, and decrease with the increasing ventilation speeds and vehicle speeds.

INTRODUCTION

There are lots of air pollutants in tunnel due to the automobile exhaust emission, and the ingredients in automobile exhaust are very complex, mainly including CO, NOx, HC and particle matters, etc. (Chang et al., 1982; Robert et al., 1984; Bellasio, 1997; Steven et al., 1998; Johannes et al., 1998) Among these ingredients, CO is the most harmful for its highest concentration, greatest toxicity to the human health and the purifying difficulty, and the CO concentration should be controlled especially in long highway tunnel (Lei et al., 1998). It has been reported that the concentration and distribution of pollutants in the tunnel are mainly affected by the longitudinal ventilation speed and the automobile exhaust emissions intensity, and 43%~70% pollutions were diluted through tunnel ventilation equipment (Deng et al., 2003; Chen, 2006). However, these above studies focused on the pollutions concentration and diffusion characteristics under the tunnel operating conditions, and little has been reported on the pollutions distribution characteristics.

Chung et al. (2007) applied the standard κ-ε equations to establish a numerical model to study the diffusion and distribution of pollutions during the tunnel operation. Shinichi et al. (1998) developed a three-dimensional Taylor-Galerkin numerical model, and simulated the air quality near roadway tunnel portals. However, there are always ventilations during the tunnel operation, and they obviously cause the strongly swirling flow. Zhou (2012) found that a certain degree distortion may occur if the standard k-ε model is applied to simulate strongly swirling flow, curved wall flow or curved streamline flow, and RNG k-ε model was more applicable.

In this paper, RNG κ-ε model was applied to establish a numerical model for simulating the diffusion and distribution of pollutions in tunnel and the
effects of vehicle speed and ventilation speed on the diffusion and distribution characteristics of CO were investigated.

NUMERICAL SIMULATION MODEL

2D models are established for the tunnel horizontal section, as shown in Fig.1. The model width is 11m, and the model length is 55m. There are three vehicles, named as Vehicle 1, Vehicle 2 and Vehicle 3 respectively. The vehicle model is a 2m×1.5m rectangle, and the exhaust pipe is 0.05m in diameter. The left side of the model is ventilation entrance, and the right side is ventilation outlet.

![Figure 1. 2D model of horizontal section.](image)

The initial CO concentration in the tunnel is set as zero, the initial air temperature is 27°C, the exhaust temperature is 527°C, and the traffic flow is assumed to be uniform and saturated. The tunnel wall and vehicle wall are defined as adiabatic wall, the tunnel ventilation entrance and exhaust pipe are defined as velocity inlet and the ventilation outlet is defined as the outflow. According to the real tunnel operation situation, the RNG κ-ε two-equation flow model is adopted.

In order to analyze the effects of ventilation and vehicle speeds on the distribution of automobile exhaust in the tunnel, three ventilation speeds are set as 0m/s, 2m/s and 4m/s, and the vehicle speeds were set as 10m/s, 15m/s and 20m/s. When simulating the effects of vehicle speeds, the interval time between two vehicles is set as 3.5s, 4s, 4.5s, and the distances between two vehicles are 35m, 60m and 80m. So, the lengths of the tunnel models are reset as 55m, 85m and 100m. CO contents in the exhaust and the exhaust emission rate is in correspondence to the vehicle speeds, which are finalized in Table 1.

<table>
<thead>
<tr>
<th>Items</th>
<th>Vehicle speed/m·s⁻¹</th>
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<tbody>
<tr>
<td></td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>CO content/%</td>
<td>0.7</td>
<td>0.38</td>
<td>0.32</td>
</tr>
<tr>
<td>Emission rate/%</td>
<td>2.5</td>
<td>3.7</td>
<td>5.2</td>
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</table>

RESULTS AND DISCUSSIONS

Effects of ventilation speed on CO distribution

When the ventilation speed is 0m/s, CO distributions in the horizontal section are shown in Fig.2. Fig.2 (a) is the distribution under single vehicle traffic, and Fig.2 (b) and (c) are the distributions under the saturated traffic flow. It is found that CO distributions are similar under different traffic flow, and the more traffic volume, the higher CO concentration. Therefore, CO distribution after Vehicle3 passed through the tunnel is considered as the CO distribution under the saturated traffic flow in the tunnel for subsequent analysis.
Figure 2. CO horizontal distributions after (a. Vehicle 1, b. Vehicle 2, and c. Vehicle 3) pass through the tunnel at the ventilation speed of 0m/s.

When the ventilation speeds are 0m/s, 2m/s, 4m/s, CO distributions under the saturated traffic flow in the horizontal section are shown in Fig.3. CO mostly distributes in the central area located 20m behind Vehicle3. Take the locations 5m, 10m, and 15m and 20m behind Vehicle 3 for example, CO distributions along the model width are shown in Fig.4.

Figure 4. CO horizontal distributions under the saturated traffic flow at the ventilation speeds of (a. 0m/s, b. 2m/s, and c. 4m/s).
It is found that most of CO distributes in the central tunnel area behind Vehicle 3, and the CO concentration increases in this area with the increasing ventilation speeds while the CO concentration decreases in the both side areas (about 0-3m and 8-11m from the tunnel wall). Meantime, CO concentration is
higher at the location closer to vehicle. CO concentrations in the both side areas are far lower than in the central area, and decrease with the increasing ventilation speeds. When the ventilation speed increase to 4m/s, the CO concentration in the side areas are almost zero. It is to say the ventilation in tunnel has an inhibiting effect on the lateral diffusion of CO, and it is good for pedestrian’s health especially in the mix-used tunnel for people and automobiles.

Effects of vehicle speed on CO distribution

Assuming there is no ventilation in the tunnel, three vehicles pass through the tunnel at the speeds of 10m/s, 15m/s and 20 m/s respectively, and the distances between two vehicles are set as 35m, 60m and 80m correspondingly, CO distributions in the horizontal section are shown in Fig.5. When the vehicle speed is 10m/s, the distance between two vehicles is short, and CO concentration is high. When the vehicle speed increase to 15m/s and 20m/s, the distance between the two vehicles are longer, and CO concentration is obviously lower. As the vehicle speed increases, CO distribution shows the noticeable wave distribution, which is because the high-speed traffic causes the strong vortex airflow near the tunnel wall.

![CO distribution in the horizontal section at the vehicle speeds of (a) 10m/s, (b) 15m/s and (c) 20 m/s.](image)

**Figure 5.** CO distribution in the horizontal section at the vehicle speeds of (a) 10m/s, (b) 15m/s and (c) 20 m/s.

Taking several locations behind Vehicle3 for example, CO distributions along the model width are shown in Fig.6.
Figure 6. CO distribution along the model width at different vehicle speeds.

When the vehicle speed is 10m/s, CO concentrations considerably vary along the model width at the location 10m behind Vehicle 3, and the distribution is high in the middle area and low in the both sides. The highest concentration is $9 \times 10^{-4}$ while the lowest value is $1 \times 10^{-4}$. At the location 20m behind Vehicle 3, the lateral difference reduces and there is almost no difference at the locations 30m and 35m behind Vehicle 3. When the vehicle speed increases to 15m/s,
there is also a great difference along the model width at the location 10m behind Vehicle 3, but the difference is reduced by half compared with the vehicle speed of 10m/s. At the location 20m and 30m behind Vehicle 3, there are still the differences, which are less than the location 10m behind Vehicle 3.

However, at the location 40m, 50m and 60m behind Vehicle 3, CO distribution is low in the middle area but high in the both sides inversely. The same regularity is observed when the vehicle speed increases to 20m/s. The results show that CO concentration is higher at the location closer to Vehicle3, and decreases with the increasing vehicle speed. CO concentrations along the model width are different, which is high in the middle area and low in the both sides at the location within 40m behind Vehicle3 while low in the middle area but high in the both sides at the location 40m beyond Vehicle 3, and the difference decreases with the increasing vehicle speed.

CONCLUSIONS

(1) In the tunnel, CO distributions are similar under different traffic flow, and the more traffic volume, the higher CO concentration. CO concentration is higher at the location closer to vehicle.
(2) CO mostly distributes in the central area of tunnel located 20m behind the last vehicle. In this area, CO concentration increases with the increasing ventilation speeds, but decreases with the increasing vehicle speed.
(3) In the both side areas of tunnel, CO concentrations are far lower than in the central area of tunnel, and decrease with the increasing ventilation speeds and vehicle speeds. The ventilation in tunnel has an inhibiting effect on the lateral CO diffusion.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Nos. 51378073 and 51408043), the Department of Science & Technology of Shaanxi Province (Nos. 2016KJXX-69 and 2016ZDJC-24) and the Special Fund for Basic Scientific Research of Central College of Chang’an University (Nos. 310821153502 and 310821173501). The authors gratefully acknowledge their financial support.

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