Large eddy simulation of smoke flow in a real road tunnel fire using FDS

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Abstract

Numerical study is carried out using large eddy simulation to study the heat and toxic gases released from fires in real road tunnels. Due to disasters about tunnel fires in previous decade, it attracts increasing attention of researchers to create safe and reliable ventilation designs. In this research, a real tunnel with 10 MW fire (which approximately equals to the heat output speed of a burning bus) at the middle of tunnel is simulated using FDS (Fire Dynamic Simulator) for different ventilation velocities. Carbone monoxide concentration and temperature vertical profiles are shown for various locations to explore the flow field. It is found that, with the increase of the longitudinal ventilation velocity, the vertical profile gradients of CO concentration and smoke temperature were shown to be both reduced. However, a relatively large longitudinal ventilation velocity leads to a high similarity between the vertical profile of CO volume concentration and that of temperature rise.

Keywords: Large eddy simulation, Tunnel fire, Smoke flow, Fire Dynamic Simulator.

Introduction

Growth of people and transportation systems, and also disasters happened in industrial cities forces the governments to look much serious to underground constructions. The history won't forget the subway tunnel fires in Daegu of Korea in February, 2003, killed 198 people, a fire in Mont Blanc tunnel in March,1999, killed 39 people, a fire in Tauern tunnel in May, 1999, killed 12 people and a corridor fire at the Hillhaven Nursing home of Norfolk, Virginia in October, 1991, killed 10 people [1- 4]. Statistics show that 75% - 85% of deaths are related to the toxic gases resulted from fires [5]. This denotes the weak and an unfavorable design of ventilations system on behave of removing CO and some other mortal gases. Discharging the heat and gases should be done properly by the ventilation system from the time fire is started. The transport of heat may be different from CO in a channel fire environment, due to their different controlling mechanisms. The information about the relationship between the distribution of CO and temperature is very important for dealing with issues related to channel fire safety, e.g., (1) localization of fire detection systems and selection of heat sensors or gas sensors; (2) fire hazard evaluation, concerning that people escaping through the lower parts of the channel in a fire emergency.
Many investigations have been devoted for ventilation studies using full scale and model scale experiments. Due to much cost related to the measuring instruments of fire researches, numerical methods have been developed to simulated the real scenarios may occur in tunnels. There are few researches about CO profiles in case of fire, as we know the importance of fire gases distribution in tunnels. A recent numerical study has declared that there could be considerable discrepancies among the longitudinal distribution of CO concentration and temperature rise in a tunnel fire [6].

Newman's experimental study was performed in a longitudinally ventilated horizontal mine passage [7,8], and the results showed that the vertical profile of CO concentration follows temperature rise at the locations downstream of the fire source. Yang *et al* [9, 10] used model scale experiments to recognize the carbon monoxide stratification and thermal stratification. The results showed that the relationship between CO stratification and thermal stratification depends on heat loss from smoke flow to walls and a larger longitudinal ventilation velocity leads to a slower decay in temperature rise along the longitudinal direction. However, longitudinal ventilation has a small effect on the longitudinal profiles of normalized CO volume concentration. The vertical profile of smoke temperature and that of CO concentration, and their difference, will be influenced by the longitudinal ventilation in a tunnel fire which also needs to be discovered. In this research, a real tunnel of 600m length × 10m width × 7m height and a 10MW fire at the middle is simulated using FDS. Two ends of the channel is open and 1,2 and 4m/s ventilation velocities are used to characterize the CO and temperature vertical profile at different locations.

Numerical Simulation

Numerical CFD simulations carried out using FDS, a popular tool for fire and related researches and transportation of toxic species developed by National Institute of Standards and Technology (NIST), USA. Large Eddy Simulation (LES) modeling for buoyant driven flow is used with second order accurate in numeric space and time differences. A refined Smagorinsky sub-grid turbulence model is used in FDS to predict the sub-grid scale motion of viscosity, thermal conductivity, and material diffusivity [11, 12]. The dynamic viscosity defined in FDS is

$$\mu_{ijk} = \rho_{ijk} (C_s \Delta)^2 |S| \tag{1}$$

where C_S is an empirical Smagorinsky constant, Δ is $(\delta x \delta y \delta z)^{1/3}$ and

$$|S| = 2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{\partial w}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 \tag{2}$$

The term $|S|$ consists of second-order spatial differences averaged at the grid center. The thermal conductivity k_{ijk} and material diffusivity D_{ijk} of the fluid are related to the viscosity μ_{ijk} in terms of the Prandtl number, *Pr*, and Schmidt number, *Sc*, by:

$$k_{ijk} = \frac{c_p \mu_{ijk}}{\Pr}; (\rho D)_{ijk} = \frac{\mu_{ijk}}{Sc} \tag{3}$$

In the Smagorinsky sub-grid model, the constant C_S is an important but sensitive parameter. It is flow dependent and has been optimized over a range from 0.1 to 0.25 for various flow fields. It was also reported that taking C_S as 0.2 gave good predictions for buoyancy-driven flow [13] and a channel flow [14].

In this study, the real tunnel of 600 meter length, 10 meter width and 7 meter height is used [6]. Schematic view of the tunnel is shown in Fig. 1. At the middle of the tunnel, a 10MW square pool fire which approximately equals to the heat output speed of a bus is placed. A mixture fraction combustion model is used in the LES simulation of FDS. The two ends of the tunnel were both set to be naturally opened with no initial velocity boundary condition specified for these openings. A cold inert wall boundary condition, which was defaulted in FDS to consider the convective heat loss through the wall, was set for the internal tunnel surface. The ambient temperature was set to be 20°C.

In LES simulation, the grid size is an important factor to be considered. The basic methodology of LES is that accuracy increases as the numerical mesh is refined. However, smaller gird size gives more detailed information of the turbulent flow but needs more computation resource and longer computing time. In a former report [15], a grid system with smaller grids of 0.13m assigned for near fire region as complex chemical and physical process taking place there and coarser grids of 0.4m for other spaces was validated [15] to give good prediction for a full scale tunnel fire simulation by FDS. In this study, a finer grids system was used. A smaller grid size of 0.125m (8 grids in 1 meter) was set for the near fire region, which covers the region from 10 m upstream to 10m downstream from the fire source (domain size of 20 m (L) × 10 m (W) × 7 m (H)). The grid size for other spaces was set uniformly to be 0.2m (5 grids in 1 meter). All the simulations were run for a total simulation time of 900s when the flow field was shown to be already quasi-steady.

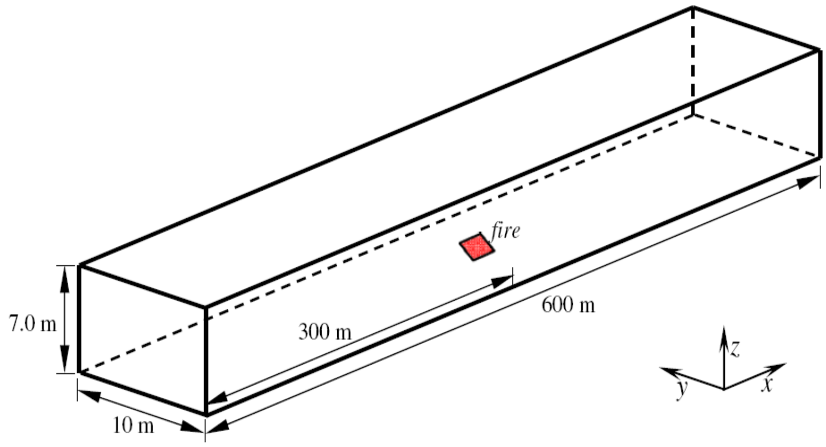

Figure 1. Isometric view of tunnel

For the justification of the convergence of the CFD simulation, the Courant- Friedrichs-Lewy (CFL) criterion is used in FDS [10, 11]. This criterion is more important for large-scale calculations. In FDS, the estimated velocities are tested at each time step to ensure that the CFL condition is satisfied [11, 12]:

$$\delta t.MAX\left(\frac{u_{ijk}}{\delta x},\frac{v_{ijk}}{\delta y},\frac{w_{ijk}}{\delta z}\right)<1 \tag{4}$$

The initial time step is set automatically in FDS by the size of a grid cell divided by the characteristic velocity of the flow. During the calculation, the time step is varying and constrained by the convective and diffusive transport speeds to ensure that the CFL condition is satisfied at each time step [11, 12]. The CFL numbers during the iterations were in the range of 0.35 to 0.97, all less than the criteria value of 1. The CFL convergence criteria was satisfied.

Results

The vertical profiles of CO concentration and temperature at 350m, 400m, 450m, 500m and 550m downstream from the inlet (50m to 250m downstream the fire source) are typically plotted for longitudinal ventilation velocities of 1, 2 and 4m/s. Values from 29 positions were sampled for each vertical profile with intervals of 0.25m. Fig. 2 shows the temperature rise in vertical direction for various location of 1m/s ventilation velocity. It is clear the smoke temperature is much more than fresh air so it has lower density. The maximum temperature occurs beneath the ceiling for every location. It is also shown that the temperature decays through the channel in which the heat loss to the ambient through the ceiling is responsible for this phenomenon. The vertical profile of CO volume concentration is shown in Fig. 3. Due to low value of the smoke density, the concentration of this species at the highest position is much more from other vertical points. Fresh air entrainment to the plume reduces the concentration of Carbon Monoxide along the tunnel. It has been shown that the reduction of CO is correlated through harmonic equations [6].
Fig. 4 indicates the vertical profile of temperature for 2m/s ventilation velocity. It can be inferred that with the increasing longitudinal velocity, average temperature of position is lowered due to large amount of entrained fresh air. In other words, heat can be removed from boundaries or

decreased through air entrainment, but the CO concentration can't be removed from the walls. Though, the temperature vertical profile decays faster than CO concentration profile. With the decrease in height, CO volume concentration seems to decay more slowly than the temperature.

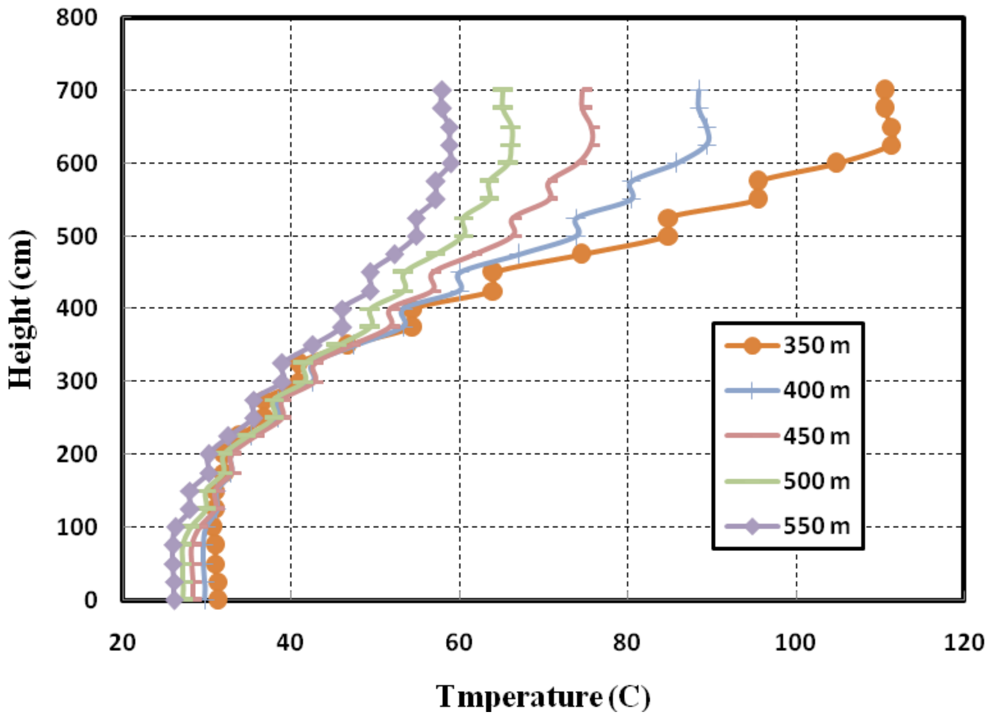

Figure 2. Vertical temperature profile for 1 m/s ventilation velocity

Fig. 5 demonstrates the vertical profile of CO for 2m/s ventilation velocity. It can be seen that decay of CO longitudinal profile occurs faster with the increase of ventilation velocity. As the ventilation velocity is increased the turbulence mixing of the fresh air and smoke layer enhances. Entrainment of air will be raised at such these conditions reducing the concentration of toxic gases. But increasing the ventilation velocity is not recommended, typically. Fresh air will enhance the rate of combustion resulting much more average temperature in the tunnel.

Fig. 6 and 7 show the vertical profiles of temperature and CO volume concentration, respectively. These figures show that for larger ventilation velocity, profiles approach each other much more. It means that with the increase of the longitudinal ventilation velocity, the vertical profile gradients of smoke temperature and CO concentration were both reduced. This is due to the fact that the entrainment of fresh air into the plume and the smoke layer was enhanced by higher longitudinal ventilation. So vertical profile of temperature and CO concentration is similarly reduced. Large ventilation velocity is responsible for large Reynolds number showing turbulent fluid flow. So the effects of turbulent transfer become more significant, which enhance the mixing in the vertical direction.

A larger ventilation velocity results in the heat loss from smoke flow accounting for a smaller percentage of the total energy flow rate. This decreases the differences in boundary conditions between the transport of CO species and that of heat. This reason contributes to the similarity between the vertical profile of temperature rise and that of CO volume concentration at the conditions with relatively larger ventilation velocity. It is notable that 1m/s and 2m/s ventilation velocities are below the critical ventilation velocity and 4m/s is above that value. This means that back layered smoke for lower velocities, is drawn downstream the fire at higher velocities. In spite of CO increment for higher velocities, air entrainment is the controlling mechanism for faster decay of CO profile vertically.

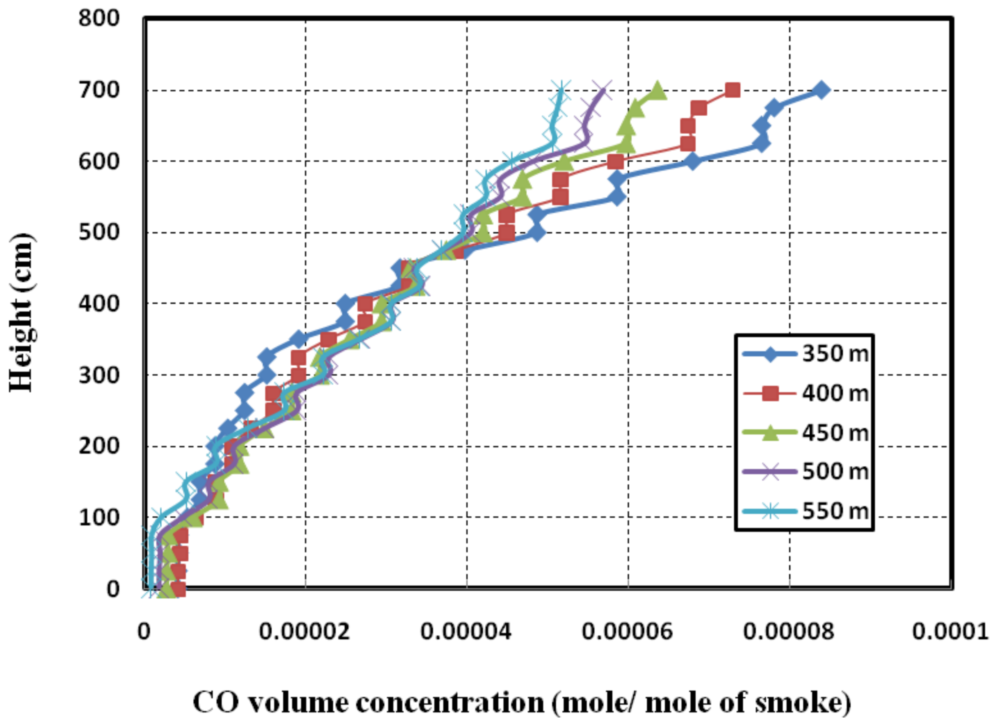

Figure 3. Vertical Carbon monoxide volume concentration for 1 m/s ventilation velocity

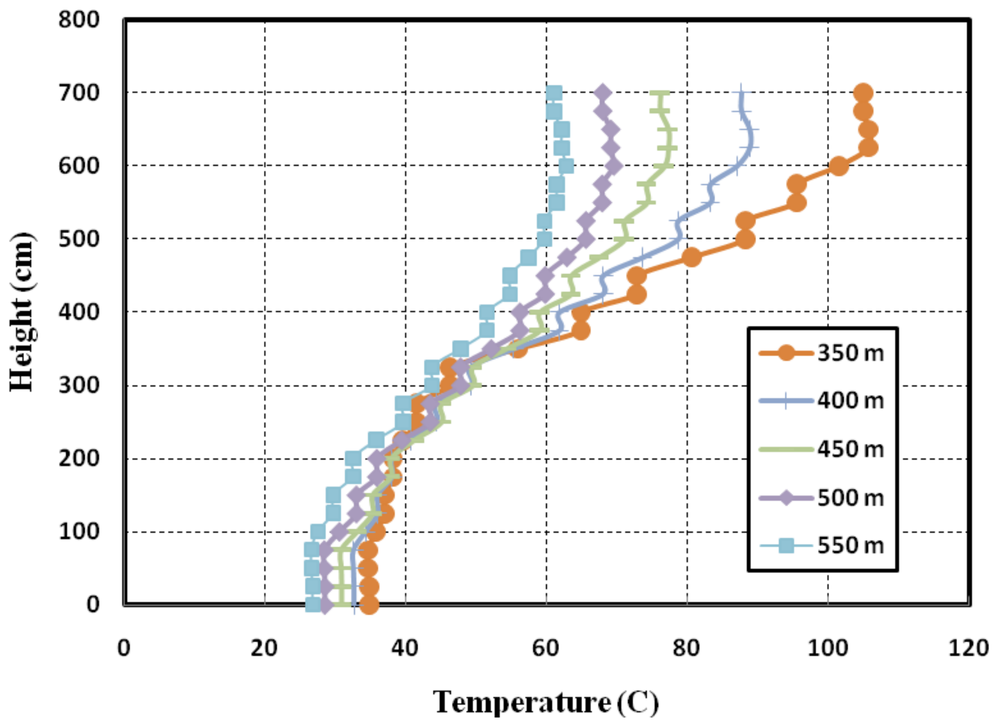

Figure 4. Vertical temperature profile for 2 m/s ventilation velocity

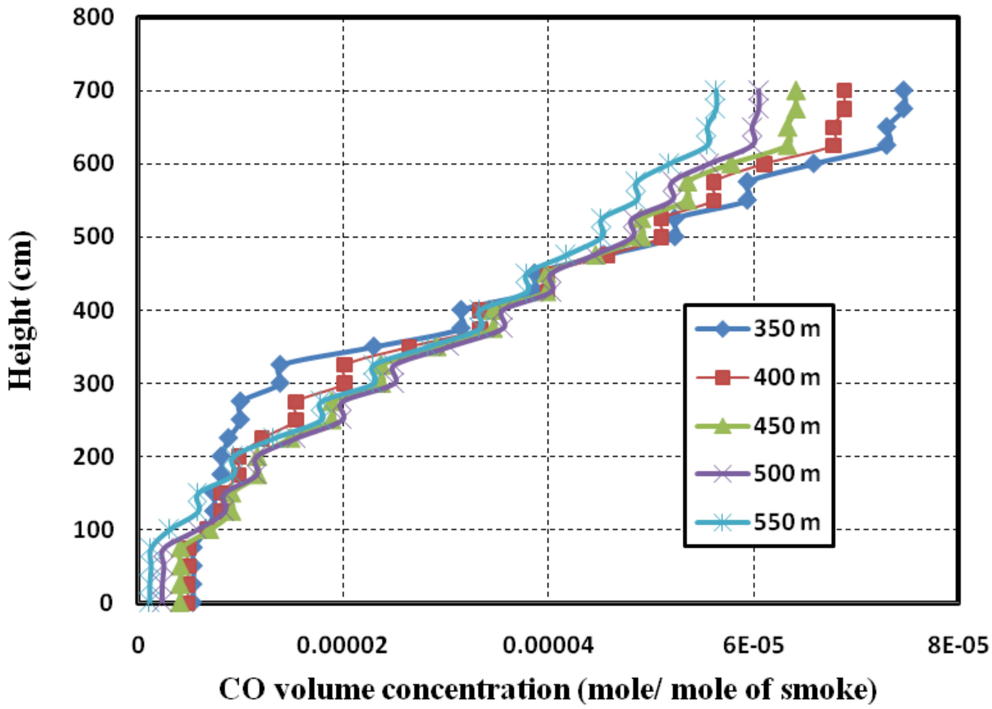

Figure 5. Vertical Carbon monoxide volume concentration for 2 m/s ventilation velocity

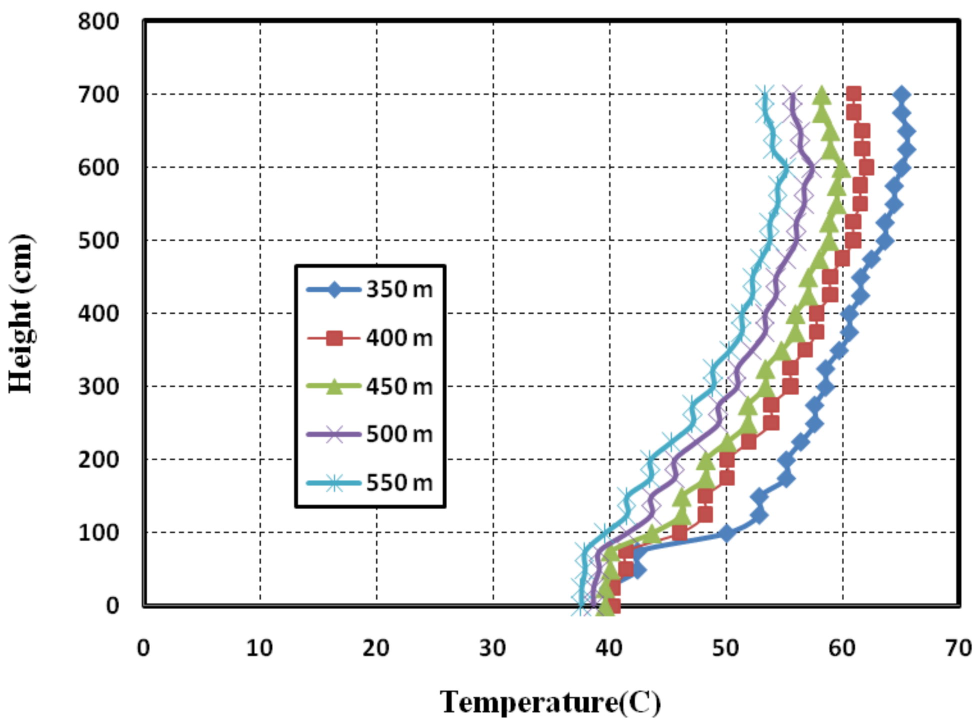

Figure 6. Vertical temperature profile for 4 m/s ventilation velocity

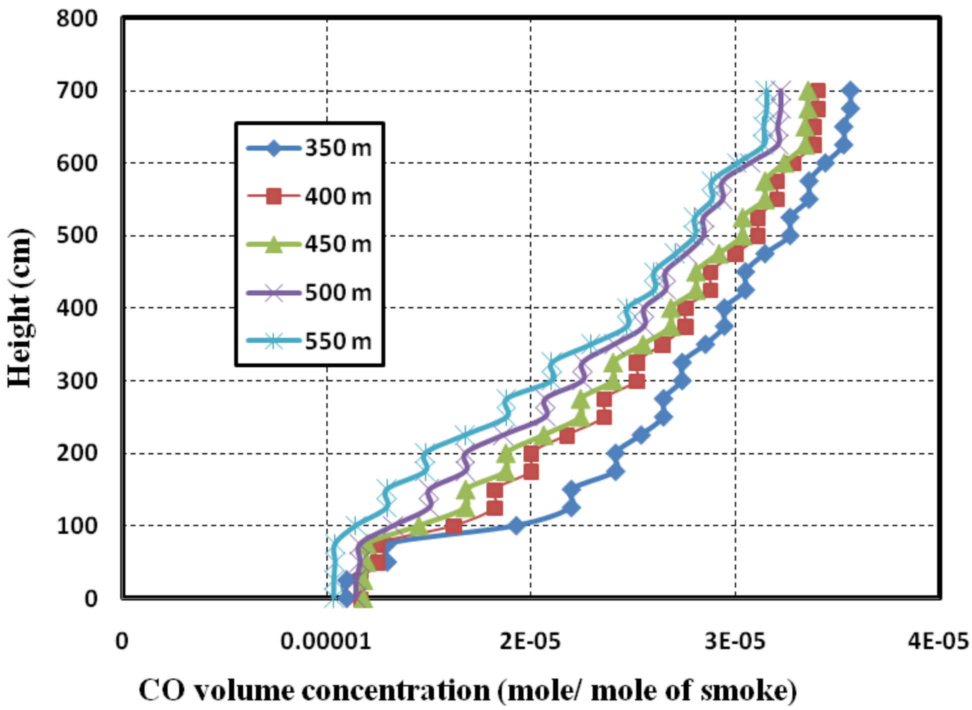

Figure 7. Vertical Carbon monoxide volume concentration for 4 m/s ventilation velocity

Conclusion

A numerical study is performed to investigate the CO and temperature profiles for a real tunnel fire of 600m length × 10m width × 7m height and a 10 MW fire at the middle using FDS. Results showed that in the vertical direction, CO volume concentration decays more slowly than temperature rise with the decrease in height. Longitudinal ventilation has significant effects on the longitudinal profiles of temperature rise. With the increase in longitudinal ventilation velocity, the temperature rise decays more slowly with the increase in the distance from the fire origin. However, the longitudinal ventilation has little effect on the longitudinal profiles of CO volume concentration. In the conditions with small longitudinal ventilation velocities, there remain differences between the vertical profiles of CO volume concentration and those of temperature rise. In the conditions with relatively strong longitudinal ventilation, the vertical profiles of CO volume concentration show similarity to those of temperature rise.

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