A NUMERICAL STUDY ON THE EFFECT OF SMOKE CONTROL SYSTEMS IN SUBWAY STATION FIRES

S.R. Lee, D.G. Nam and S. Moriyama
Department of Architecture, Waseda University, Tokyo, 169-8555, Japan

ABSTRACT

In this study, numerical simulations were carried out to analyze the effect of the smoke extraction system and fire shutters in subway station fires using FDS 4.0. CFD validation was carried out by comparison between numerical results and experimental results. Temperature distribution under the ceiling showed a good agreement with experimental results approximately within 10°C. Numerical predictions were performed in the island-type subway station in case of a kiosk fire. Case that smoke extraction systems both the platform and the concourse were operated and fire shutters were closed was most effective on smoke control.

KEYWORDS: Subway station fires, Smoke movement, Ventilation, Fire shutters, CFD

INTRODUCTION

With rapid growth of economy and the population, many cities worldwide adopted subway as a major means of transportation. Many subway lines have been constructed in large cities to ease the traffic problems. Such positive characteristics as speed, stability, punctuality, efficiency, and less pollution have made subway a major means of public transportation.

The February 18, 2003 incendiary fire at Daegu Jungang-Ro station in Korea resulted in 192 dead and 148 wounded[1]. Without making immediate notification of fire and taking urgent action to prevent it from spreading, great loss of lives and properties will be suffered as demonstrated by the Daegu incident. Underground fires have distinctive characteristics unique from other kinds. First of all, it is difficult for evacuees to act and escape promptly because of limited space. It is also likely that the limited feed of inflow air will generate a large amount of smoke and toxic gases. High temperature smoke and heat, therefore, can be spread very rapidly. It is hard for the fire brigades to approach the accident. It is also difficult to grasp the inner situation or to find the ignition point. A delay in fighting the fire is often expected, therefore. Many emergency facilities should be installed within convenient reach to minimize physical damages and losses of human lives.

Methods to analyze smoke movement in an underground fire include full-scale experiments, reduced-scale experiments and numerical simulations. Because a full-scale fire test is performed in a real-state situation, it provides the most useful data among these methods mentioned. The full-scale test, however, involves high costs, time-consuming procedures, and has a risk of fire. A reduced-scale experiment or a numerical simulation can be used as an alternative. By applying the scaling law, a reduced-scale experiment can reproduce the flow characteristics of a real fire situation. Whereas this method can save time and costs, careful attention must be paid to the application of a scaling factor between the prototype and the model. A benefit of using a numerical simulation is that the simulation can be analyzed repeatedly under various conditions. Because a simulation contains many assumptions, however, all the numerical results should be validated, especially by full scale data.

Recent research on underground fires[2-4] shows that smoke control is the critical factor in saving lives under fire. In order to establish an appropriate fire protection plan, the key characteristics of underground fires must be properly understood. The purpose of this study is to verify the predictions of the CFD code by making a comparison across different sets of full-scale experimental data for subway station fires. At the same time, this study also estimates the effects of ventilation. The results can be used in many areas, particularly in establishing a fire protection system or planning.

EXPERIMENTAL SUBWAY STATION

Smoke movement tests were conducted using simulated fire sources on a subway platform in a station currently in service[5]. The station is located in Tokyo, Japan, and is a center-platform type station. The outline of the station is detailed in Table 1. The platform is located on the B-2 level, and connected to a concourse on the B-1 level by stairways and escalators. The station is equipped with a mechanical ventilation system, which extracts smoke on the platform and concourse by reversing the fan. The tests were conducted at midnight to avoid any conflicts with traffic services. Fire shutters are installed in the stairway connected to the platform and to the concourse. During fire fighting activities, shutters are normally kept open until the evacuation from the platform is completed. Keeping the shutters open would prevent from coming into the concourse. Keeping them open would also help avoid hindering the evacuation of passengers.

TABLE 1. Outline of subway station

Type	Ceiling Height (m)	Width (m)	Ventilation system	
			Platform	Concourse
Center platform	2.8	16	Exhaust	Exhaust

Six-square methanol trays with 0.5 m were used in the fire tests. We used methanol as a fuel. Preliminary tests confirmed that each tray had an approximately 80 kW heat release rate. The fire source intensity was set at 480 kW. Since this heat release rate represents only the early stage of fire, numerical simulations were used to predict the impact of more realistic fires. Ventilation capacity of the platform was approximately 130,000 m^3/h. Eighty-four vents were installed under the ceiling with 5 m intervals. Ventilation capacity of the concourse was approximately 23,000 m^3/h. Twenty-one vents were installed under the ceiling. These in the concourse, however, were not operated in the experiment.

Also measured were the distribution of temperature, velocity and static pressures. K-type thermocouples, hot-wire velocity probes, pressure and other tubes were all set on length-adjustable poles. Hot-gas movement was visualized with smoke candles located near the fire sources. Experiment lasted up to 12 minutes. Table 2 presents the test condition of smoke movement.

TABLE 2. Test condition of smoke movement tests

Time	Smoke extraction	Shutters
0:00	Off	Closed
2:00	On	Closed
5:00	On	50 cm closed
8:00	On	Open

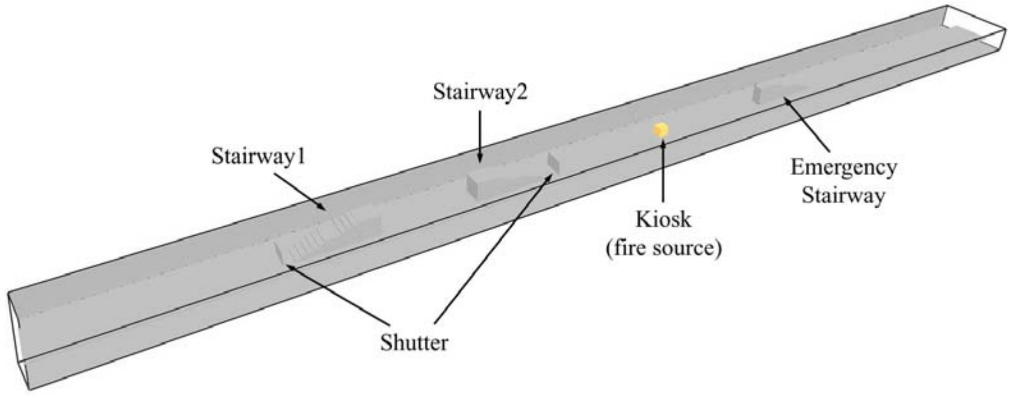
NUMERICAL SIMULATION

The Fire Dynamics Simulator, being developed at NIST, is designed to study fire behavior and to evaluate the performance of fire protection systems. A number of studies of fire dynamics have validated FDS[6–9]. An approximate form of Navier–Stokes equations appropriate for low Mach number applications is used in the model. The approximation involves filtering out acoustic waves while allowing for large variations in temperature and density. To handle sub-grid scale convective motions, we used a large eddy simulation technique, where large-scale eddies are computed directly and sub-grid scale dissipative processes are modeled. Fire-driven flows in FDS were simulated by LES turbulence model, the mixture fraction combustion model, the finite volume method of radiation transport for a non-scattering gray gas, and conjugate heat transfer between wall and gas flow. A heat release rate per unit area was applied to the fuel surface and treated as an average value. The wall heated up due to the transfer of radiative and convective heat from surrounding gas. The heat transfer to the wall was calculated by prescription of the thermal conductivity. Details of the numerical model can be found in Ref. 10.

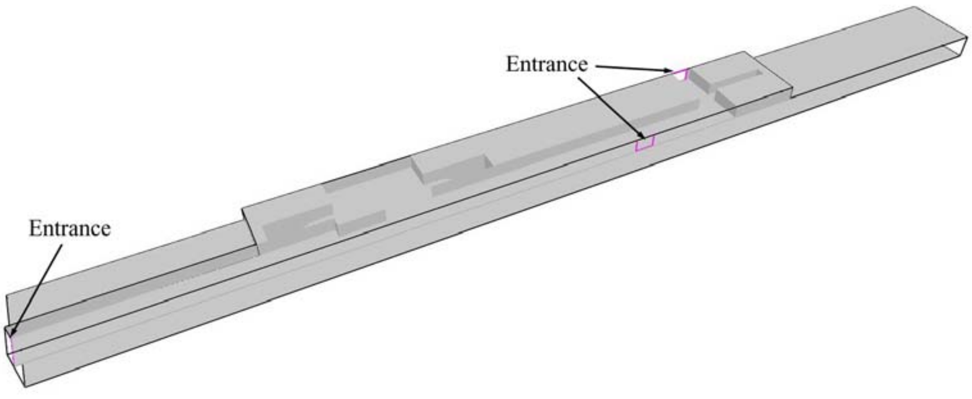
Simulations were carried out in the platform and in the concourse with dimensions of 210 m × 16 m × 8.1 m. The layout of subway station is shown in Fig. 1. In this study, optimum grid resolution was selected by grid independent tests. The number of meshes was about 1,150,000. A pressure boundary condition was given in the tunnel exit. Simulations lasted up to 600 s under seven sets of scenarios designed to evaluate different smoke control methods (see Table 3). It was assumed that a fire started from a kiosk (2 m × 2 m × 2 m) on the platform. The kiosk was located 25 m from the second stairway on the platform floor, which was located on the center line of the station. Fire intensities were set at 5 MW and 10 MW with polystyrene. An unsteady fire followed the t-square fire model, and grew from zero to 5 MW within 163 s in a form of an ultra-fast fire[11]. The computing time required approximately 65 hours, using Pentium-IV 2.1 GHz PC.

TABLE 3. Scenarios of fire simulation

Case No.	Fire Intensity(MW)	Ventilation		Shutters	
		Platform	Concourse	50cm	Full
1	5	Off	Off	Open	Open
2	5	On(120sec)	Off	Open	Open
3	5	Off	Off	Closed(180sec)	Closed(300sec)
4	5	On(120sec)	Off	Closed(180sec)	Closed(300sec)
5	5	On(120sec)	On(300sec)	Closed(180sec)	Closed(300sec)
6	5	On(120sec)	On(300sec)	Open	Open
7	10	On(120sec)	On(300sec)	Closed(180sec)	Closed(300sec)



(a) Platform level



(b) Concourse level

FIGURE 1. Layout of subway station

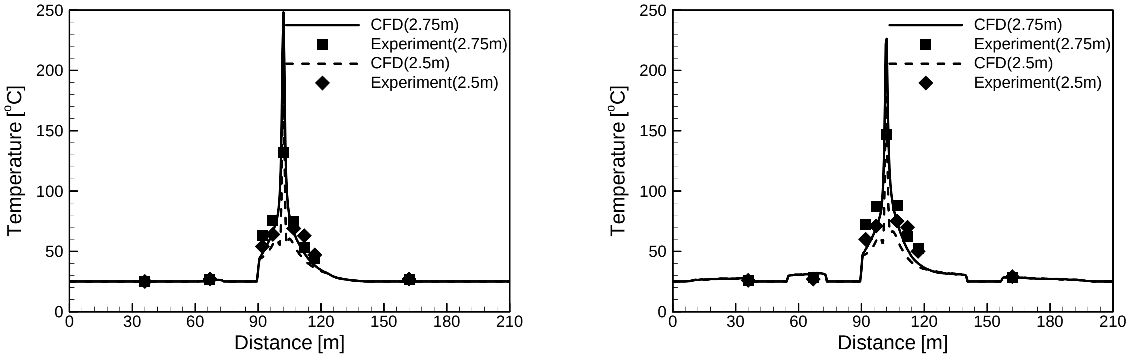
RESULTS AND DISCUSSION

In order to validate the model’s ability to predict the smoke movement in a subway station, temperature distributions under the ceiling and vertical temperature distributions at 17 m from the second stairway were compared with the experimental results.

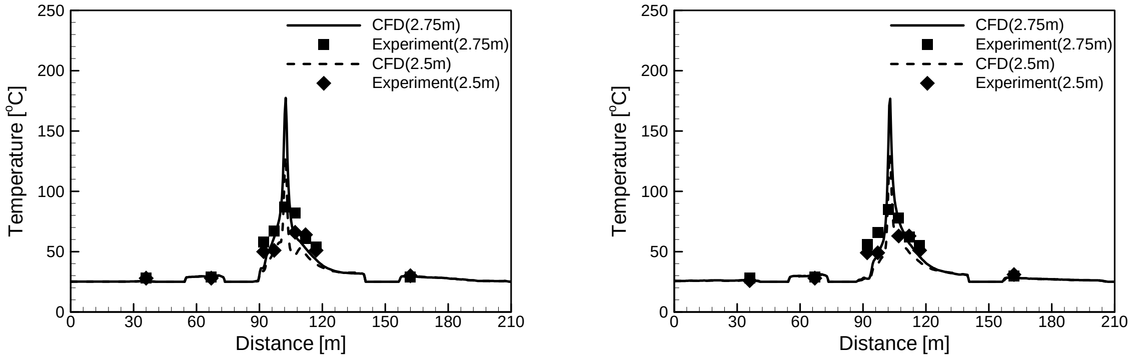
Figs. 2 and 3 show the comparison results. Due to the heat loss to the surroundings, the smoke temperature was dropped as the smoke moves along the platform ceiling. Simulation results are in good agreement with the experimental results within about a 10°C difference except for the upper part of the fire source. These findings support the idea that FDS code can be applied to subway station fires.

Fig. 4 presents how soot density in Case 1 was distributed over time. As a hot smoke moves outward under the ceiling surface, smoke transfers energy by conduction to the relatively cool adjacent ceiling surface and by convection to the entrained air. Smoke movement is retarded by friction forces from the ceiling surface above and by turbulent momentum transfer to the entrained air from below. Due to the flow and the heat transfer, the smoke continuously decreases velocity. Smoke reaches the concourse in about 150 s and fills the entire platform in 200 s. The platform and the concourse are filled with the smoke in approximately 400 s.

If there is no operation of a mechanical ventilation system, evacuees may be exposed to a great danger. Numerical simulations were thus carried out to evaluate the effectiveness of the smoke extraction system and fire shutters installed in the experimental subway station. Fig. 5 shows the temperature distributions at 1.5 m and 2.5 m above the platform floor and 5 m from the platform wall after 600 s. When fire shutters are closed without mechanical ventilation, temperature in the left side of the kiosk is higher than that with natural ventilation at 1.5 m height. When smoke extraction systems operate, temperature shows a similar result and lowered maximum about 30°C compared with that with natural ventilation regardless of opening or closing shutters.

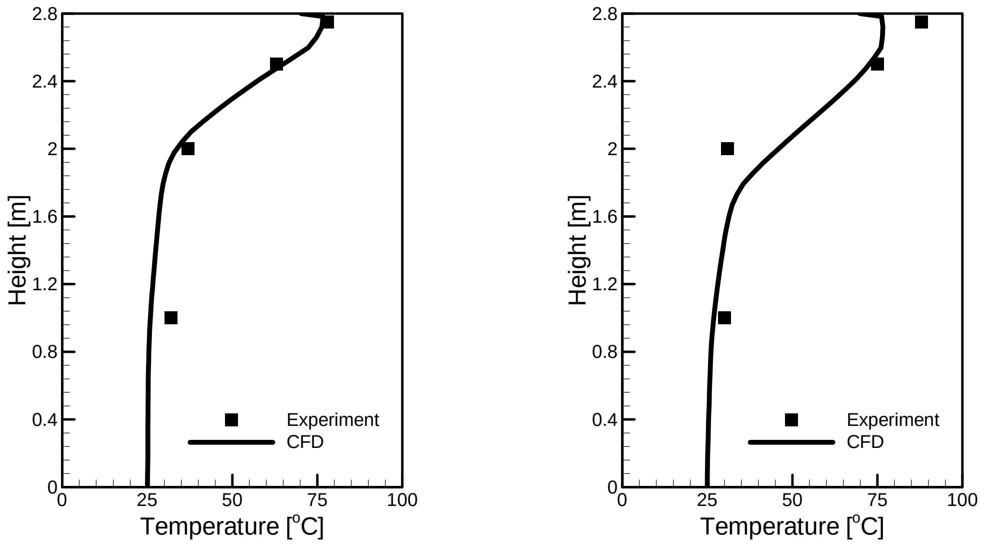


(a) 120 s (b) 300 s

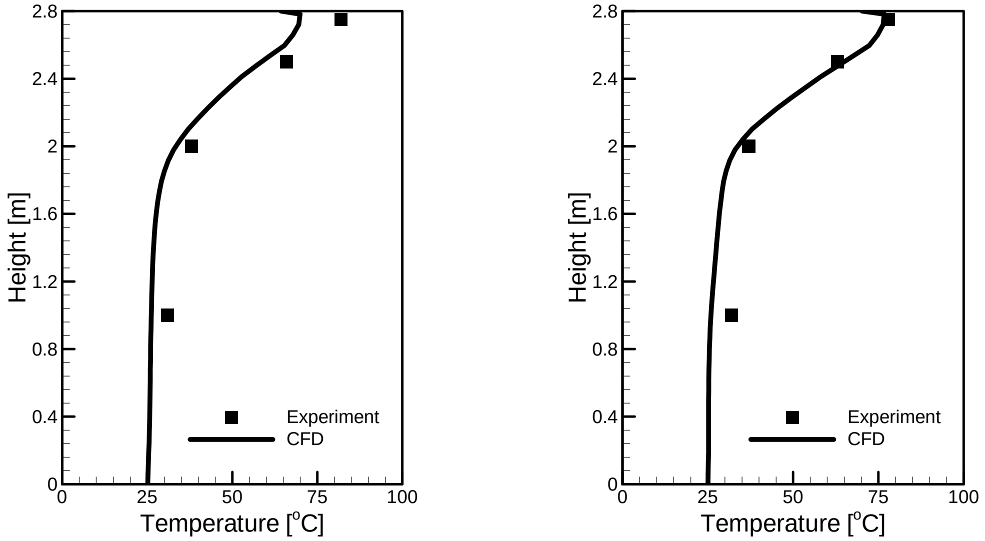


(c) 480 s (d) 720 s

FIGURE 2. Temperature distributions under the ceiling of the platform



(a) 120 s (b) 300 s



(c) 480 s (d) 720 s

FIGURE 3. Vertical temperature distributions at the platform

Fig. 6 shows temperature distributions at 1.5 m and 2.5 m above the concourse floor and between stairways. Temperature drops as the smoke extraction system operates. Temperature also drops as the shutters close. Temperature in Case 3 is slightly lower than it is in Case 2. Closing the shutter is more effective than operating the smoke extraction system in reducing the temperature in the concourse level. When shutters are closed, the smoke extraction system in the concourse has little influence on the temperature.

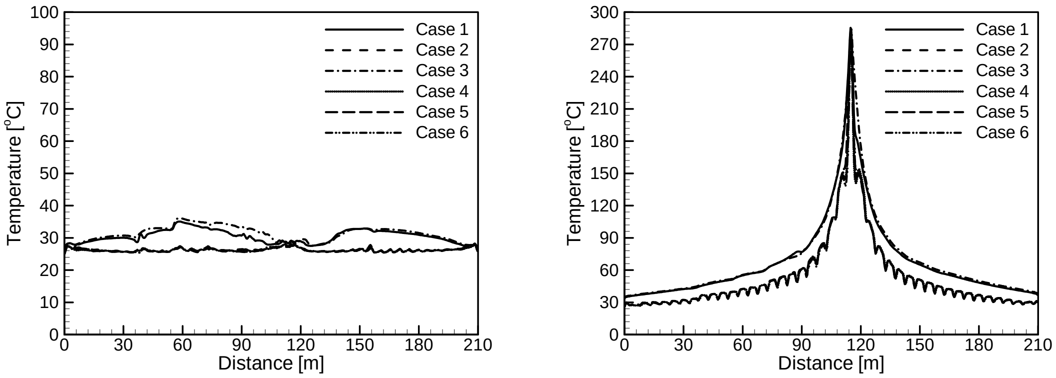
(a) 100 s

(b) 150 s

(c) 200 s

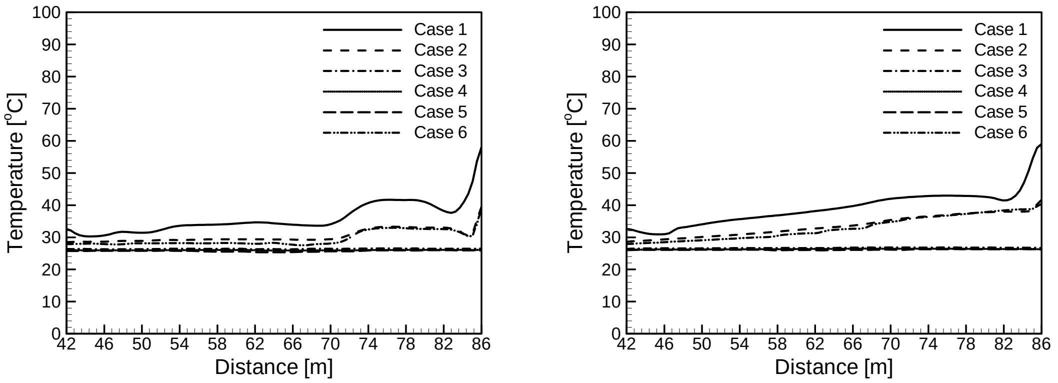
(d) 400 s

FIGURE 4. Distribution of soot density with time



(a) y = 1.5 m (b) y = 2.5 m

FIGURE 5. Temperature distribution in the platform at 600 s



(a) y = 1.5 m (b) y = 2.5 m

FIGURE 6. Temperature distribution in the concourse at 600 s

Fig. 7 shows the temperature contours of the Cases 1 and 5 at 600 s. The comparison of Cases 1 and 5 on the temperature contour supports the effectiveness of smoke extraction systems and fire shutters.

Fig. 8 presents CO concentration distributions 1.5 m and 2.5 m above the platform floor and 5 m from the platform wall. When fire shutters are closed without the smoke extraction system in operation, CO concentration in the left side of the kiosk is higher than that with natural ventilation at 1.5 m and 2.5 m height. CO concentration around the kiosk is lower than other regions at 1.5 m height, because cool fresh air is entrained the lower part of the fire source. When smoke extraction systems are in operation, findings tend to be similar to the result of temperature. CO concentration dropped below 200 ppm at 2.5 m height by mechanical ventilation.

Fig. 9 shows CO concentration distributions at 1.5 m and 2.5 m above the concourse floor and between stairways. The results show that CO concentration dropped below about 60ppm by operating the smoke extraction system or by closing fire shutters. CO concentration contours of the Cases 1 and 5 at 600 s are shown in Fig. 10. The comparison of Cases 1 and 5 on the CO concentration supports the effectiveness of smoke extraction systems and fire shutters.

(a) Case 1 (y = 5 m)

(b) Case 5 (y = 5 m)

(c) Case 1 (y = 8 m)

(d) Case 5 (y = 8 m)

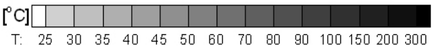
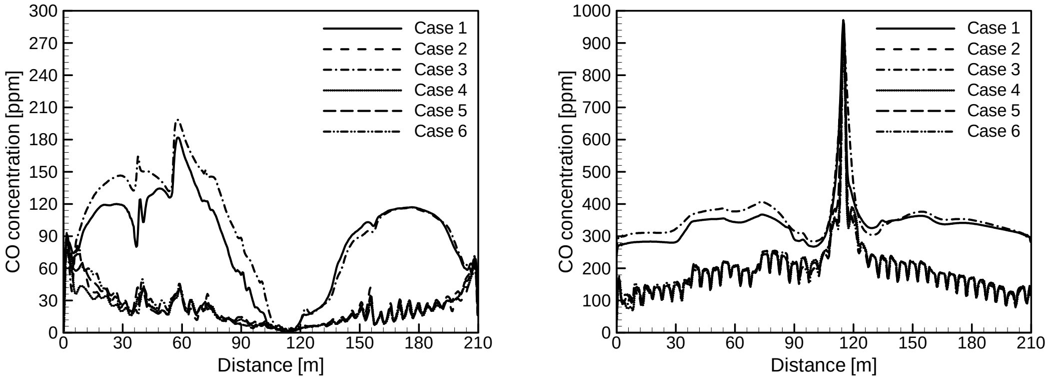
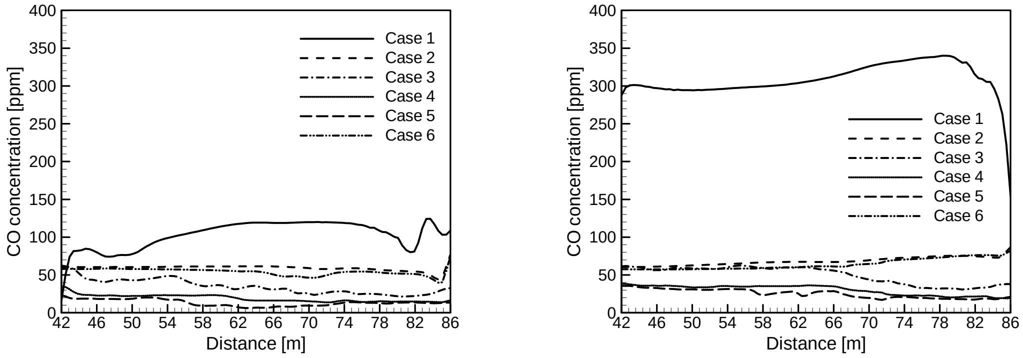


FIGURE 7. Temperature contours of Case 1 and Case 5



(a) y = 1.5 m (b) y = 2.5 m

FIGURE 8. CO concentration distribution in the platform at 600 s



(a) y = 1.5 m (b) y = 2.5 m

FIGURE 9. CO concentration distribution in the concourse at 600 s

(a) Case 1 (y = 5 m)

(b) Case 5 (y = 5 m)

(c) Case 1 (y = 8 m)

(d) Case 5 (y = 8 m)

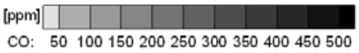


FIGURE 10. CO concentration contours of Case 1 and Case 5

Results from Case 5 turn out to be the most effective in smoke control. A numerical experiment was performed in order to confirm the effect of fire size under the same ventilation used in Case 5 with a 10 MW fire. Figs. 11 and 12 show a comparison between Cases 5 and 7 on the temperature and CO concentration measured at 5m from the platform wall. At 1.5 m height, is there a small (or little) difference between the two cases. Regardless of fire size, temperatures are similar around the platform ends because of the air incoming from the outside of the platform. At 2.0 m height, temperature of 10 MW fire is at most 15^{o}C higher than that of 5 MW fire. As the fire size increases from 5 MW to 10 MW, CO concentration goes up from 200 ppm to 400 ppm at 2.5 m height except for the vicinity of the fire source.

Fig. 13 presents the distribution of soot density at 600 s in Case 7. Soot does not reach the left entrance of the concourse by operating the smoke control system. Smoke control effectiveness can be demonstrated by a comparison with Fig. 4 (d).

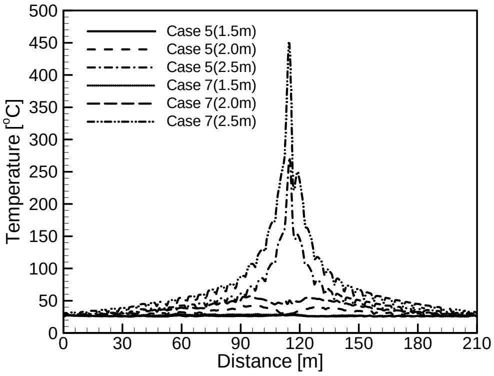


FIGURE 11. Temperature comparison between Case 5 and Case 7

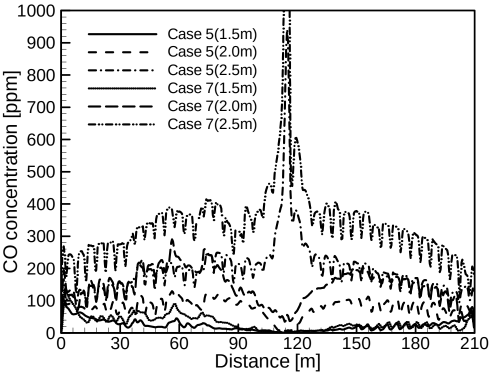


FIGURE 12. CO concentration comparison between Case 5 and Case 7

FIGURE 13. Distribution of soot density at 600 s in Case 7

CONCLUSION

This study conducted numerical simulations in order to validate the FDS code and to examine the effectiveness of the ventilation method in controlling smoke movement in subway fires.

Temperatures are in good agreement with experimental results within about a 10°C difference. Temperatures and CO concentrations are affected by the method of ventilation. When the smoke extraction system is in operation and fire shutters are closed, temperatures and CO concentrations are most effectively controlled in both the platform and the concourse. These findings may offer useful considerations in establishing a fire protection system and planning.

ACKNOWLEDGEMENTS

This work was supported by the Korea Research Foundation Grant funded by the Korean Government (KRF-2006-214-D00021).

REFERENCES

1. Hong, W.H., “The Progress and Controlling Situation of Daegu Subway Fire Disaster”, 6th Asia-Oceania Symposium on Fire Science and Technology, 28-46, Dague, Korea, 2004.
2. Modic, J., “Fire Simulation in Road Tunnels”, Tunnelling and Underground Space, 18:5, 525-530, 2003.
3. Gao, P.Z., Liu, S.L. Chow, W.K. and Fong, N.K., “Large Eddy Simulations for Studying Tunnel Smoke Ventilation”, Tunnelling and Underground Space, 19:6, 577-586, 2004.
4. Vauquelin, O. and Wu, Y., “Influence of Tunnel Width on Longitudinal Smoke Control”, Fire Safety Journal, 41:6, 420-426, 2006.
5. Moriyama, S., Hasemi, Y., Okazawa, N., Nam, D.G. and Ding, W., “Smoke Movement Tests in Subway Stations Actually in Service – Smoke Movement Characteristics in Center Platform Stations in the Early Stage of a Fire”, Bulletin of Japan Association for Fire Science and Engineering, 56:23-35, 2006. (In Japanese)

6. Ma, T.G. and Quintiere, J.G., "Numerical Simulation of Axi-symmetric Fire Plumes: Accuracy and Limitations", Fire Safety Journal, 38:5, 467-492, 2003.
7. Kim, S.C. and Ryou, H.S., "An Experimental and Numerical Study on Fire Suppression Using a Water Mist in an Enclosure", Building and Environment, 38:11, 1309-1316, 2003.
8. Zhang, W., Hamer, A., Klassen, M., Carpenter, D. and Roby, R., "Turbulence Statistics in a Fire Room Model by Large Eddy Simulation", Fire Safety Journal, 37:8, 721-752, 2002.
9. Lee, S.R. and Ryou, H.S., "A Numerical Study on Smoke Movement in Longitudinal Ventilation", Building and Environment, 41:6, 719-725, 2006.
10. McGrattan, K.B., Fire Dynamics Simulator (version 4) - Technical Reference Guide, NIST, 2006.
11. NFPA 92B, Guide for Smoke Management Systems in Malls, Atria and Large Area, National Fire Codes, 1991;10.