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OPTIMIZATION OF SMOKE VENTILATION STRATEGY IN A TYPICAL UNDERGROUND METRO STATION FIRE

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ABSTRACT

Compartment fire is an unwanted event that needs to be accessed carefully in order to ensure the safety of occupants and structures. This study emphasizes on fire and smoke spreads in a typical underground metro station. Underground metro station usually has a geometry that will direct smoke in the same direction as the evacuation course. Thus, to secure safety of the passengers, the rate of the smoke spread and stratification should be reduces by well designed smoke ventilation systems. This paper examines the performance of ventilation configurations proposed for a typical underground metro station design. The study was carried out by using numerical model of Fire Dynamics Simulator version 6.0 and fire test in 1:25 bench scale of a typical metro underground station. Three ventilation configurations will be provided in this paper namely, mechanical ventilation, natural ventilation, and hybrid ventilation. The objective of this study is to formulate ventilation strategies in order to optimize the smoke handling capacity for lengthening the available safe egress time (ASET) during a fire event in a typical underground metro station. The discussion will also include the effect of hybrid ventilation on the occurrence of the pulsating phenomenon of smoke flow.

INTRODUCTION

Nowadays, mass rapid transportation has growth rapidly in many cities of the world, including their constructions as underground metro systems. By paying attention to numerous catastrophic tunnel fire accidents involving underground metro systems, such as at King’s Cross Underground Station (London, 1987), “Deutsche Oper” Underground Station (Berlin, 2000), Heinrich – Heine – Allee Underground Station (Dusseldorf, 1991), and Daegu Metro Station (Korea, 2003), pointed out the important of improving fire prevention and smoke ventilation strategies. In fact, these records raised attentions from many researchers to improve the design and fire safety aspects of underground structure including underground metro station.

Fire in tunnel and underground metro station has been intensively researched, especially in terms of the smoke and other toxic gases (e.g. Carbon Monoxide) spread and distribution. It is considered that smoke properties and CO concentration as the most important parameters affecting human safety in case of fire in tunnel or underground structure (Fourneau et al., 2013). The distribution and propagation of smoke spread, longitudinal CO concentration and gas temperature distribution have been extensively researched in literature (Ji et al., 2012; Lonnermark and Ingason, 2005; Regev et al., 2004; Tsai et al., 2010; Weng et al., 2014). Various phenomenon which affects smoke spread in a tunnel regarding smoke bifurcation flow, effect of inertia and buoyancy force, and turbulence characteristics are well investigated in literatures (Chen and Leong, 2011; Vaux and Pretrel, 2013; Wei et al., 2013). In addition, countermeasures of the hazardous condition caused by fire in term of ventilation strategy to provide safe condition for the evacuees were proposed in literature (Betta, 2010; Harish and Venkatasubbaiah, 2014; Luo et al., 2013a, 2013b), in this case longitudinal ventilation, air curtain formation, jet van application, and natural ventilation were applied.

Related to underground metro station fire, (Gupta, 2012) conducted a series of fire simulation using Fire Dynamics Simulator (McGrattan et al., 2014a, 2014b) to study mechanical ventilation improvement in order to diminish the hazard from horizontal dispersion of smoke. The prediction of fire – induced smoke spread in an underground metro station had been studied by Gao et al. (2012a). The results indicated that mechanical ventilation significantly control the spread of smoke in horizontal direction, while natural ventilation effectively hindering vertically downward movement of the smoke. In addition, the natural ventilation represented by the opening at the roof of the atria structure will be more effectively exhaust smoke when the fire source located relatively close to the atria.

In case of fire, atria can assist smoke management system in order to control downward movement of the smoke that depends on the capacity of atria smoke – filling which process had been simulated by Chow (1995) in various typical shapes of the atria. On the other hand, locating an opening at the atria roof or ceiling, can effectively provide natural ventilation to control fire – generated smoke and heat. The impact of the extraction rate in consequence of the atria ceiling opening and the geometrical parameters of the atria on the smoke and heat control had been thoroughly investigated by Tilley and Merci (2013). The application of natural ventilation by the opening at the atria ceiling combined with mechanical ventilation in case of fire at underground metro station can effectively control smoke spread and provide safe egress for the evacuation to proceed (Gao et al., 2012b). This study proposed a ventilation mode which incorporated mechanical and natural ventilation simultaneously which is referred to as hybrid ventilation. However, the objective of the ventilation system cannot be accomplished without a proper ventilation strategy. Luo (2014) proposed an effective ventilation strategy at three storey underground metro station while the fire located at the second floor. The ventilation strategy stated that smoke exhausted by means of hybrid ventilation and the confinement of smoke will be assisted by supplying fresh air from the lowermost level. In this ventilation strategy, ventilation at the uppermost level, either in supplying or exhausting mode, is not operated.

In this paper, fire – induced smoke spread was simulated in a typical two storey underground metro station under various conditions including the impact of different mechanical ventilation strategy, stairs geometry, platform screen door opening, atria structure and its ceiling opening. Fire source was located at the lowermost level to introduce more credible fire condition by considering the direction of the smoke flow which is in the similar direction with the evacuation course. Later on, the hybrid ventilation mode which applied mechanical and natural ventilation simultaneously (Gao et al., 2012) is also studied in this work. In addition, a short discussion on the pulsation phenomenon of the smoke flow will be indicated.

PHYSICAL MODEL

The station model used in this study is a typical two storey underground metro station with length of 130 m (note: for future use, the station box can be extended up to 220 m long), width of 13 m and a total height of 10 m with free height of concourse and platform are 3 m. Thus, resulting in available space of 2 m in each station level to accommodated ventilation duct. The connection between platform and concourse level are three stairs with length and width of stairs column are 10 m and 5 m, consecutively. The physical model of the underground metro station used in this study can be clearly observed in Figure 1.

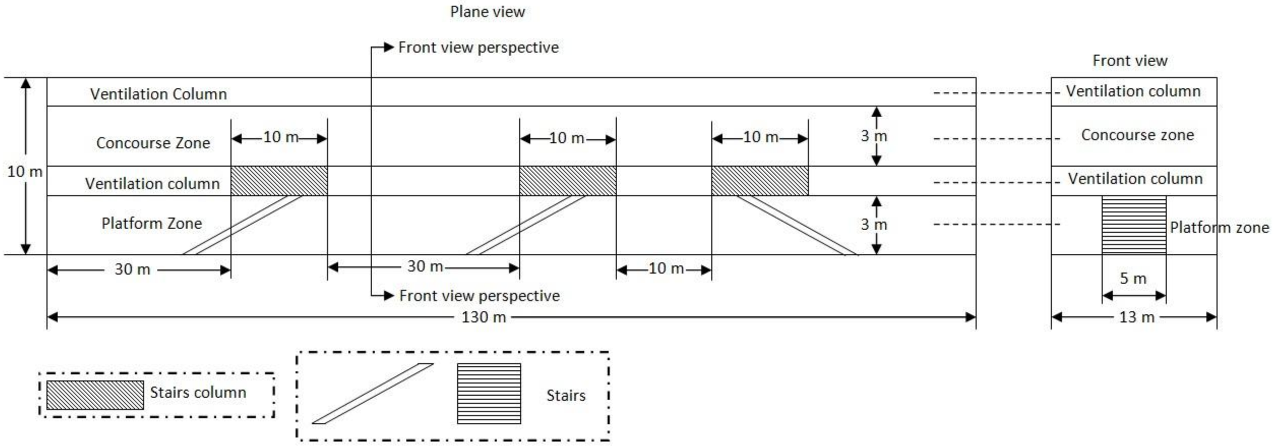


Figure 1. Schematic picture of underground metro station physical model

Lastly, there was assumed that platform level confined from the tunnel area or area outside of the station by platform screen door (PSD). The partial opening of the platform screen door and its effect on the overall condition on the station is discussed in the later section of this paper.

SIMULATION SET UP

Simulations were carried out using Fire Dynamic Simulator (FDS) of NIST version 6.0. FDS is a computational fluid dynamics (CFD) model of fire-driven fluid flow. FDS solves numerically a form of the Navier – Stokes equations appropriate for low-speed ($Ma < 0.3$), thermally-driven flow with an emphasis on smoke and heat transport from fires (McGrattan, 2014a).

The modeled geometry of the underground metro station for the numerical simulation was shown in Figure 2. The dimensions were exactly specified as in Figure 1. Two dominant material were used, namely concrete and glass pyrex. Concrete and glass pyrex were used for structure and platform screen door material, respectively. The thermophysical properties of these materials referred to Incropera et al. (2007).

In Figure 2, Fire source was also pictured and positioned between the first and second stairs. The fire heat release rate (HRR) was specified as 5 MW. The fire growth rate according to t^2 fire growth rate demonstrated in Eq. [1]. Coefficient of fire growth (α) was set as 0.1876 which indicated ultrafast fire growth (Alpert, 2002). The carbon monoxide and soot yield were specified as 0.1 and 0.01, respectively.

The simulation time was set as 1800 second and the fire source burned as long as the simulation time. This approach was taken into account to make sure that the specified ventilation either capable or not to control the smoke flow. In other word, this approach was taken to observe the effectiveness of the ventilation being considered in controlling smoke flow at relatively steady state condition.

$$\dot{Q} = \alpha t^2 \tag{1}$$

Mesh Resolution

The cell dimensions in all of the simulation were set as 0.25 m in x, y, and z coordinates direction. The mesh resolution which is the ratio between the characteristic diameter of the fire (D^*) (McGrattan, 2014a) and the cell dimension (δx, δy, δz) is considered sufficient based on its value that is ranged between 4 – 16. The validation study sponsored by US Nuclear Regulatory Commission stated that the value between 4 – 16 is sufficient for the FDS mesh resolution according to the conducted validation experiments (Stroup and Lindeman, 2013). In this paper, the calculated mesh resolution with characteristic diameter of the fire calculated from Eq. [2] is about 8.

$$D^* = \left(\frac{\dot{Q}}{\rho c_p T_\infty \sqrt{g}}\right)^{2/5} \tag{2}$$

Ventilation Configuration

In normal condition, the modeled simulation is specified to have a set of inlet and outlet to supply and exhaust air. In this simulation, the air change per hour (ACH) was set to 10 times space volume. Thus, resulting in 50700 m^3/h of supplied and exhausted air in each level. The location of supply and exhaust vent were located as depicted in Figure 3. The layout of supply and exhaust vent in concourse level were similar with the layout in platform level. The volumetric rate of supply and exhaust for each vent according to total capacity of 50700 m^3/h were 0.59 m^3/s and 1.76 m^3/s, respectively. In the following discussion, this configuration will be regarded as normal condition.

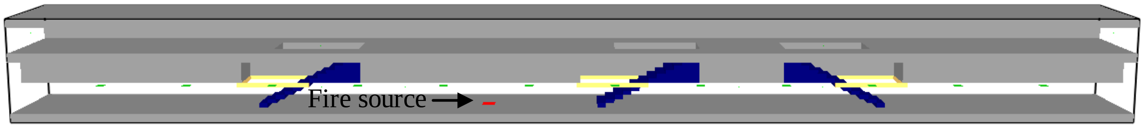


Figure 2. Modeled geometry of the underground metro station

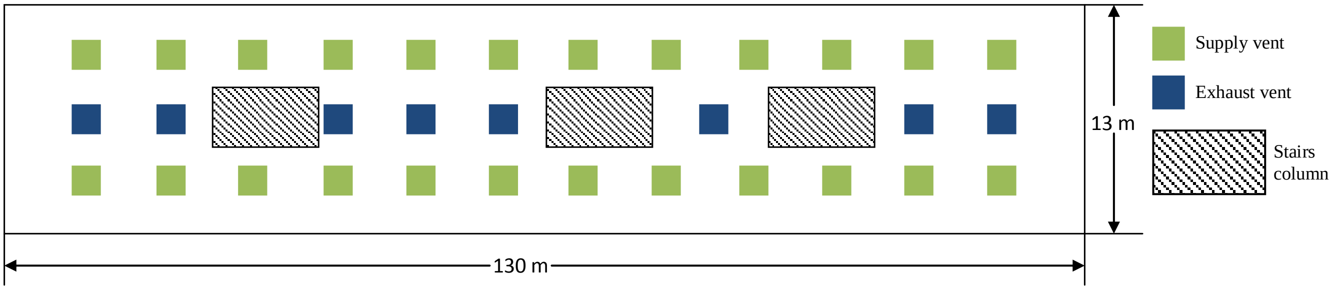


Figure 3. Supply and exhaust vents layout

In this study, several ventilation modes and other effect on the overall smoke flow as the opening of platform screen door (PSD), the impact of overhead track exhaust, the effect of additional smoke exhaust, and atria structure were observed. In this study, there are 4 ventilation modes observed, i.e. (i) normal condition, (ii) all vents in concourse level set at exhaust mode, (iii) all vents in concourse level set at supply mode, and (iv) all vents in concourse level is off or not operated.

In case of PSD partially opened, it was assumed that the openings were the opening of the PSD that used by the passengers from platform to onboard the train. In this case, the smoke will flow to the train tunnel when it has reached the PSD opening height. When smoke already passes the PSD opening, the installed Overhead Track Exhaust (OTE) which located above the train will impact the smoke flow. Hence, when the effect of smoke flow to the tunnel caused by partially opened PSD was observed, the impact of OTE would also be discussed. The total volumetric rate of OTE per train line was set as 10 ACH or 29575 m^3/hour considering tunnel volume at station area as 130 m (length), 3.5 m (width), and 6.5 m (height). Figure 4 shows position of OTE above the train line inside the tunnel. The horizontal distribution of the OTE vents along the tunnel was uniformly distributed similar to supply vents inside the platform.

To maximize smoke exhaust capacity, the authors propose an additional smoke exhaust vent which solely dedicated to exhaust fire – induced smoke in emergency situation. This additional smoke exhaust vents will be located only in platform level (Figure 5). The total volumetric rate of additional smoke exhaust vents were 5 ACH or 25350 m^3/hour.

The effect of atria structure on the overall smoke flow was also observed. The atria was attached to the station and located 42 m from the left end side of the station relative to Fig. 1. The atria dimensions are 12.5 m (length), 13 m (width), and 10 m (height). The opening of 3.5 x 3.5 m was specified at the atria ceiling to induced natural ventilation (Figure 6).

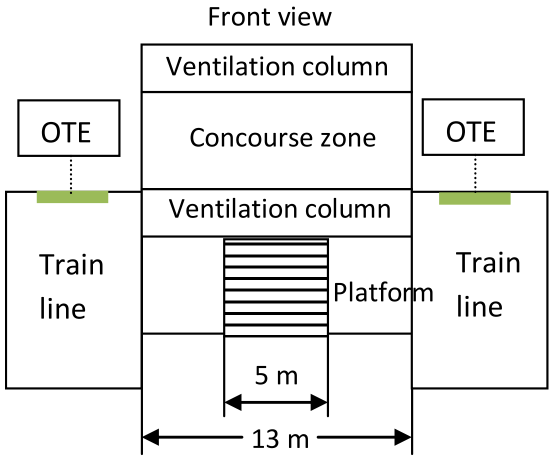


Figure 4. Schematic of OTE position above the train line in the tunnel (front view)

In order to investigate the effectiveness of smoke flow into the tunnel and optimize the utilization of OTE, this study also discusses the effect of the position of PSD opening. In this paper, two positions were studied. Firstly, the PSD opening is positioned as the normal condition which also be used when the passenger onboard the train. Secondly, the PSD opening was located at the upper fraction only, above the normal position. Figure 7 clearly illustrates the above explanation. The effect was studied when OTE and atria structure were employed.

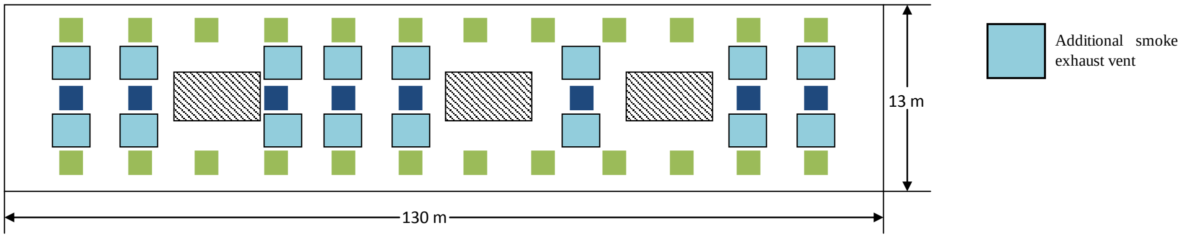


Figure 5. Location of additional smoke exhaust vent

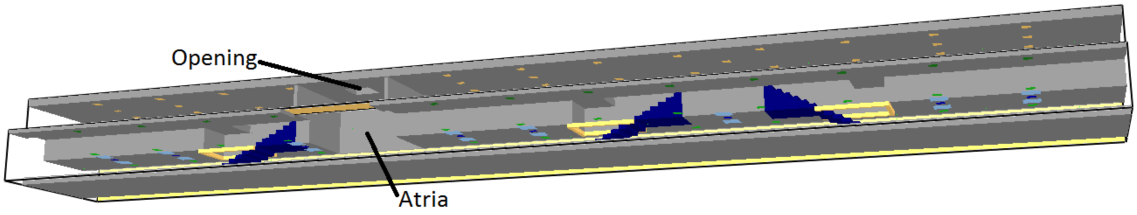
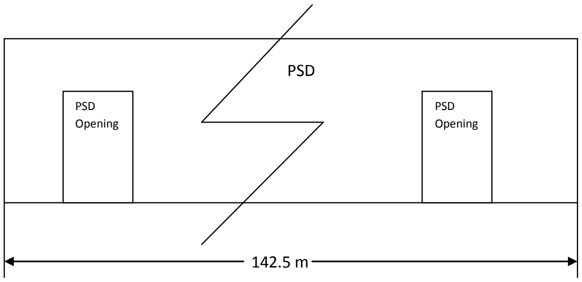
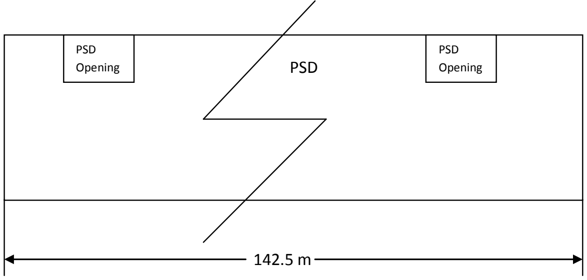


Figure 6. Attached atria in the simulation model



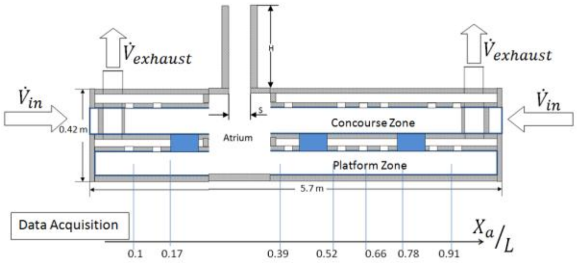
(a) Partially opened PSD



(b) Partially opened of the upper section of the PSD
Figure 7. Different position of the PSD opening in the observation of its opening location impact on the overall smoke flow

EXPERIMENTAL SET UP

Experimental works were carried out in a 1:25 reduced scale model to simulate smoke movement in a typical underground metro station fires which design with and without atria structure shown in Fig. 8. Detailed explanation of the experimental works and the dimensional analyses are available in another paper by the author (Santoso, 2014)



Experimental model of underground metro station with atria structure and the location of data acquisition
Figure 8. Experimental scaled model of underground metro station

OPERATING PARAMETERS

List of various conditions which were studied in this study is tabulated in table 2. The magnitude of the ventilation is specified as previous explanations. In case of partially opened PSD on top, the location of that opening is as illustrated in Figure 7b.

It can be seen from Table 2, in Cases 2 to 5 and in Cases 6 to 11, supply vents in platform were specified to exhaust mode. Thus, results in platform exhaust capacity of 20 ACH in total. As well as platform, in Cases 2 and 6, supply vents in concourse become exhaust. So, exhaust capacity in platform become 20 ACH in total and vice versa in Cases 3 and 7.

Table 2. List of conditions studied in this study

Case	Ventilation Mode				PSD	OTE	Additional smoke exhaust	Atria structure
	Platform Supply	Platform Exhaust	Concourse Supply	Concourse Exhaust				
Case 1	ON	ON	ON	ON	Closed			
Case 2	Become exhaust	ON	Become exhaust	ON	Closed			
Case 3	Become exhaust	ON	ON	Become supply	Closed			
Case 4	Become exhaust	ON	OFF	OFF	Closed			
Case 5	ON	ON	ON	ON	Partially opened	ON		
Case 6	Become exhaust	ON	Become exhaust	ON	Partially opened	ON		
Case 7	Become exhaust	ON	ON	Become supply	Partially opened	ON		
Case 8	Become exhaust	ON	OFF	OFF	Partially opened	ON		
Case 9	Become exhaust	ON	OFF	OFF	Partially opened	ON	ON	
Case 10	Become exhaust	ON	OFF	OFF	Partially opened	ON	ON	Exist
Case 11	Become exhaust	ON	OFF	OFF	Partially opened on top	ON	ON	Exist

RESULTS AND DISCUSSIONS

Carbon monoxide (CO) distribution was seriously taken into account in this study. Besides the increasing of temperature, CO concentration distribution and its value are major concern in fire safety risk assessment (Luo et al., 2014). In the following discussion, the observation will occasionally refer to the case number listed in Table 2 in discussing various impacts of ventilation mode, OTE, partially opened PSD, and atria structure.

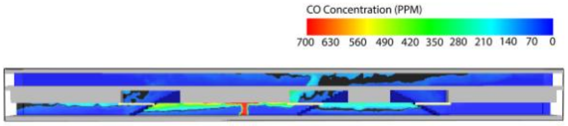


Figure 9. CO distribution of case 1 at 200 s (black color represents CO concentration of 85 ppm)

Figure 11 shows the CO distribution at 200 second with black color represents CO concentration of 85 ppm. It can be seen that almost all stairs cannot be used for evacuation in this condition especially the second stairs that have abundant CO accumulation.

When all of the vents in concourse and platform level specified as exhaust, CO distribution significantly decrease as depicted in Figure 12. The amount of CO concentration especially at 84 ppm did not occupy a significant volume of station. However, it still can be seen that smoke still capable to travel to concourse level. The effect of this capability of smoke plume to travel to concourse level on CO distribution at 10 minutes is pictured in Figure 13. Thus, the mechanical ventilation still incapable to provides safe condition for evacuation. Theoretically, 10 minutes can be considered enough for all of the evacuees to reach the assembly point. However, in actual condition where a lot of interferences exist, 10 minutes is a short time for the evacuation to proceed. It can be seen that CO distribution at 600 s on platform even reached floor level. This indicated inadequate condition on the platform level for the evacuees. In other words, all of the evacuees must leave the platform level at 10 minutes.

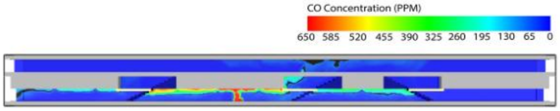


Figure 10. CO distribution of case 2 at 200 s ((black color represents CO concentration of 84 ppm)

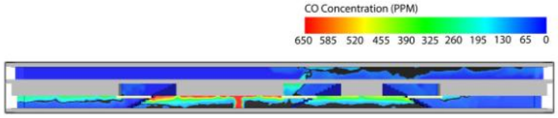


Figure 11. CO distribution of case 2 at 600 s (black color represents CO concentration of 84 ppm)

To inhibits smoke movement to the concourse level, simulation while all of concourse vents set as supply was conducted. CO distribution of this condition can be seen in Figure 14. It can be observed that supplied air from concourse level cannot inhibit smoke movement to the concourse level. Moreover, smoke accumulation occurred at second stairs caused by the contrast flow direction between smoke plume and fresh air from concourse. In long run, precisely on 10 minutes, this condition caused a greater dangerous environment as depicted in Figure 15. This hazardous condition due to supplied air from concourse that, rather that inhibits smoke flow to concourse level, diffuses smoke uniformly in station space.

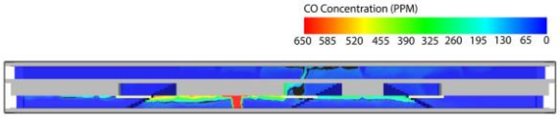


Figure 12. CO distribution of case 3 at 200 s (black color represents CO concentration of 84 ppm)

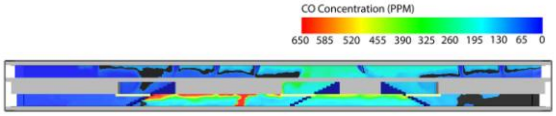


Figure 13. CO distribution of case 3 at 600 s (black color represents CO concentration of 84 ppm)

The exact value of CO distribution along station space at 2 m height from platform or concourse floor is shown by Figure 16 and 17.

It can be seen from this figure that indeed normal condition of ventilation gives relatively highest value of CO concentration either in platform or concourse level. However, despite supplying air from concourse level, it is better to set all vents in concourse level to exhaust smoke. It is proved from the observation of Figure 16 and 17 that the condition when fresh air being supplied from concourse level had a higher CO concentration value than when concourse vents totally exhaust smoke. Still, smoke plume flow to the concourse level cannot be inhibited. It considered that the incapability of ventilation to inhibit smoke plume flow either horizontally or vertically caused by relatively massive fire source in the study at hand (5 MW). Thus, the capability of ventilation to inhibit smoke plume flow to the concourse level already can be seen while fire source still in the growth phase. The comparison between all ventilation mode previously discussed added with case 4 (all ventilation vents in concourse were not operating) is pictured in Figure 18.

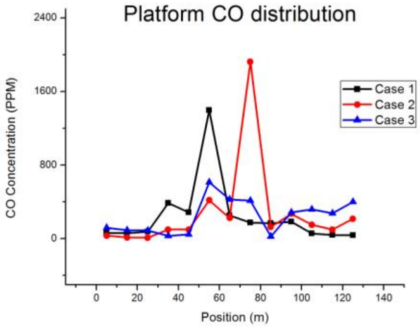


Figure 14. CO distribution in platform level at 2 m height from concourse floor

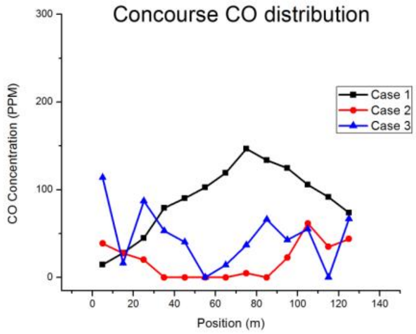


Figure 15. CO distribution in concourse level at 2 m height from concourse floor.

It can be seen from Figure 18 that, although concourse vents were not operated (case 4), smoke plume can still moved to concourse level. It indicates that platform exhaust vents of 20 ACH cannot control smoke plume movement to the concourse level in case of 5 MW fire source. The incapability of platform exhaust vent in controlling smoke movement was also illustrated by bigger smoke accumulation in case 4 when the concourse vents was not operated.

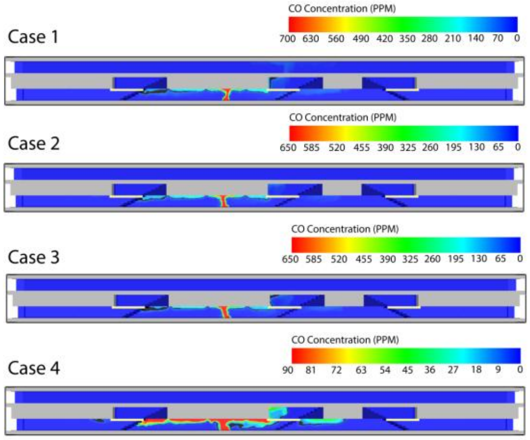


Figure 16. Comparison of CO distribution of the ventilation mode of case 1, case 2, case 3, and case 4 at 100 second while fire growth (black color indicates CO concentration of 85 ppm)

The effect of partially opened PSD and OTE

By considering the similar ventilation mode of case 1 and case 5; case 2 and case 6; case 3 and case 7; and case 4 and case 8, the impact of partially opened PSD and OTE can be successfully compared between the simulations being observed in the study.

In normal ventilation condition (case 1 and case 5), smoke plume is still capable to infiltrates concourse level. However, the volume occupied by the smoke at the concourse level was smaller than the condition where there are no openings at the PSD (Figure 19). In addition, the smoke layer height at platform level did not as low as the condition without openings and OTE. This can be caused by some fraction of smoke which pulled by OTE to the tunnel area (Figure 20).

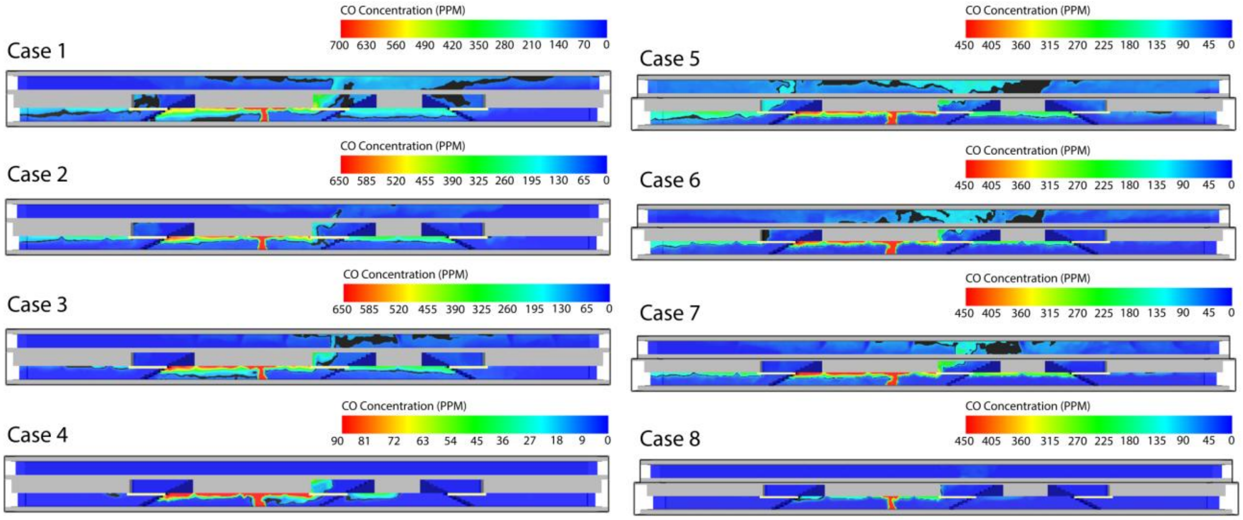


Figure 17. Comparison of the impact of partially opened PSD and OTE on CO distribution (black color indicates CO concentration of 85 ppm)

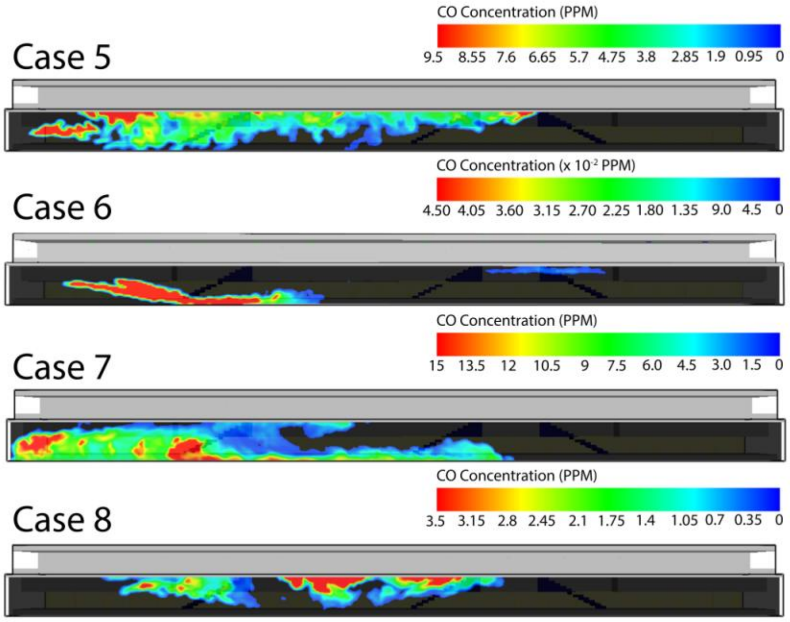


Figure 18. Comparison of the impact of partially opened PSD and OTE on CO distribution in the tunnel for case 5, case 6, case 7, and case 8 at 240 second (black color indicates CO concentration of 0 ppm)

In all – exhaust ventilation condition (cases 2 and 6), an alarming CO distribution was evident when OTE and PSD openings were applied (Figure 19). This could be caused by push effect of the fresh air that comes from the tunnel which is pulled by the exhaust vents inside the station. This condition strengthens the infiltration of smoke plume into the concourse level. Figure 20 shows a little fraction of smoke in the tunnel. That fraction of smoke was pulled or pushed to the tunnel from the left end side of the station and pulled back inside the station as pictured in Figure 21.

When all the vents at the concourse level acted as supply vent (case 3 and case 7), the CO distribution inside of the station between case 3 and 7 had little difference (Figure 19). However, relatively significant fraction of smoke pushed to the tunnel through PSD openings as depicted in Figure 20.

When there were openings at the PSD and OTE at the tunnel, the best condition occur when all the vents at the concourse is not operated. In this case, a modest fraction of smoke was pulled by OTE to the tunnel (Figure 20) and significantly reduce CO mass fraction inside the station (Figure 19).

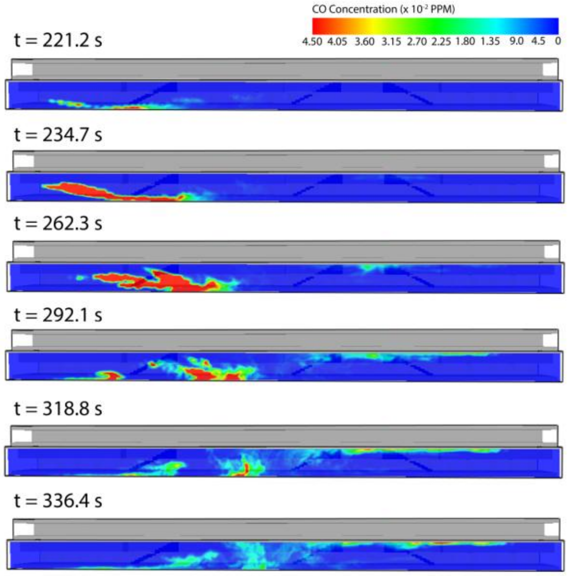


Figure 19. Fraction of smoke pulled from the left end side of the station and pulled back inside the station

To maximize the utilization of platform ceiling space, the author proposed an additional exhaust vents as explained before which indicated as case 9 in table 2. The additional exhaust vents were succesfully reduced significant CO concentration distribution in concourse and platform level as depicted in Figure 22.

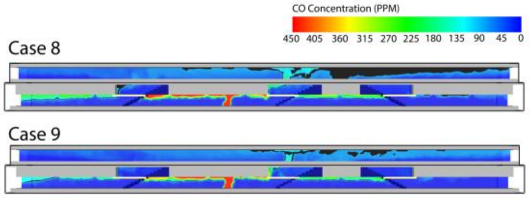


Figure 20. The effect of additional smoke exhaust at 289.3 s (black color indicates CO concentration of 85 ppm)

Hybrid ventilation which is the combination of mechanical ventilation and natural ventilation induced by the opening at the atria ceiling has positive effect on the fire – induced environment condition correspond to CO distribution level. The CO concentration distribution when there is attached atria structure is depicted in Figure 23.

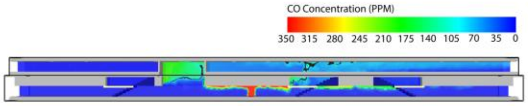


Figure 21. The impact of atria structure on the overall CO concentration distribution (black color indicates CO concentration of 85 ppm)

From the observation of Figure 23, natural ventilation caused by atria indeed had positively reduced overall CO distribution. On the other hand, atria structure also acted as temporary smoke reservoir before the smoke exhausted through the atria ceiling opening. Thus, the opening at the atria ceiling plays an important role in diminishing smoke distribution. However, the natural ventilation caused by the opening strongly depends on the smoke temperature. While smoke traveling to the atria, it will experienced cooling effect by the air entrainment which reduced smoke temperature and caused smoke to had a lower buoyant force. In a later time, the accumulation of smoke in the atria will again increase smoke temperature and consequently increase smoke plume buoyant force to increase exhaust mass flow of smoke plume through the atria ceiling opening. This pulsation is well depicted in Figure 24.

From all of the previous discussion, the impact of OTE did not effectively control smoke movement. However, by change PSD opening on top as pictured in Figure 7, OTE at the tunnel effectively exhaust smoke plume and also reducing CO concentration distribution inside the station (Figure 25). Nevertheless, it can be seen that a small fraction of smoke plume at the second stairs pulled downward. It could be caused by the inertia force of the OTE that pulled the smoke plume inside the station downward. Still, It is just a relatively small fraction of smoke plume.

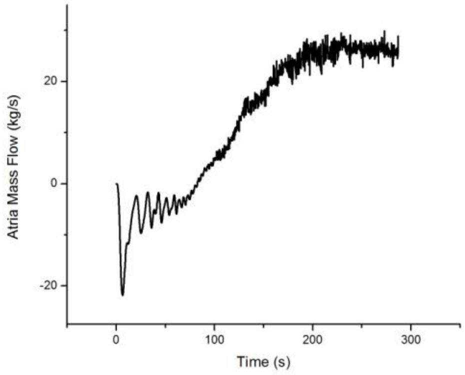


Figure 22. Mass flow in atria ceiling opening

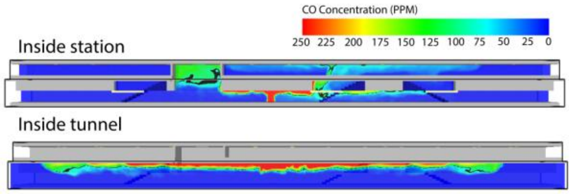


Figure 23. The impact of partially opened PSD on top (black color indicates CO concentration of 85 ppm)

CONCLUSION

From the series of conducted simulation, the optimal ventilation strategy was obtained. The most effective ventilation strategy inside the station is when all platform vents set as exhaust and concourse vents is not operated. Hybrid ventilation proved to effectively control smoke movement inside of the station. The proposed additional smoke exhaust is indeed needed to provide more effective smoke management. Lastly, to effectively utilizing OTE, PSD openings were proposed to set on top. Hence, the smoke can directly move to the tunnel with the assistance of OTE without needed to move downward first.

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