AFFORDABLE APPROACH TO THE PREDICTION OF SMOKE MOVEMENT AND EVACUATION SAFETY IN SUBWAY STATIONS

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ABSTRACT

In order to clarify predictability and affordability of predictive models of smoke movement for the application to subway stations, reproducibility of smoke movement in a subway station by a control volume zone model and CFD (Computational Fluid Dynamics) has been verified against fire tests using a station actually in service under various conditions of the shutters in the staircases between the platform and the concourse, and different modes and capacities of smoke control. This comparative study has revealed that good reproducibility can be achieved on all tested conditions by relatively simple k-epsilon CFD code with rather rough grid arrangements which can be run on PC; zone models could reproduce the smoke movement unless the staircases between the platform and the concourse is left open. The comparative study has also revealed significant advantages of the zone model in the treatment of facility conditions which are the main focus in fire safety design.

KEYWORDS: Smoke movement, Subway station, Experiments and CFD simulation

INTRODUCTION

Until recently, the validity of simulations for a subway station fire was difficult to be evaluated as there was almost no available data for a real subway station fire. To obtain some real data, in October 2003 in Tokyo, smoke movement experiments were conducted in actual subway stations currently in service. Although this experiment was limited in time, intensity and contents, essential data was collected to tune and examine the validity of the numerical calculations. Numerical studies were carried out to reproduce the experiments and then to predict fire hazard and evaluate effectiveness of such fire safety measures as smoke extraction and fire shutters in the event of more plausible, severe, fires. Both a zone model and a CFD model are adopted as simulation models. The zone model is based on the two-layer zone model, but some minor modifications were made to deal with the leeward changes of smoke layer depth within the platform. This zone model is suitable to estimate the smoke movement in the buildings which have multi-stories; however, the zone model doesn't have reliability in windy conditions which make smoke-layer unstable. In this paper, the CFD model has been applied to a station. The CFD model was tuned to reproduce the test results for both calm and windy conditions. The model was finally applied to predict smoke movement in the subway stations of more plausible fires.

VALIDITY OF THE MODEL

The numerical simulations for this research are done using a general three-dimensional computational fluid dynamics (CFD) model. Standard k-epsilon model is used and the upwind scheme has been adopted in the simulation. Table 1 explains the conditions used for the simulation. The computational domain is basically into a grid of 1000 mm × 1000 mm × 1000 mm control volumes. Additional grid points are embedded near the fire source (500 mm × 500 mm × 250 mm), stairways (500 mm × 500 mm × 500 mm) and from 1.0 m to 2.0 m height from platform floor level (1000 mm × 1000 mm × 500 mm). Heat transfer between rooms or spaces through wall is neglected. Fig. 1 shows the plan of the center platform station for simulation.

TABLE 1. Analysis conditions

Analysis Features	Transient	
Turbulence Models	k-ε / High Reynolds Number	
Precision	Double precision	
Computer	Dell Dimension XPS (CPU 3.80GHz)	
Total Mesh number	57914	
Mesh Size	Generally	1000mm×1000mm×1000mm
	FL+1m-2m	1000mm×1000mm×500mm
	Stairs	500mm×500mm×500mm
	Fire Source	500mm×500mm×250mm

(1) Boundary conditions
Walls: All of the walls are set as insulation walls.
Entrances and exits: Entrances and exits are set as pressure boundaries.
Measured speed in the experiment is converted to dynamical pressure and then given to the pressure boundary.
Tunnel exit: both left and right sides of the tunnels 100 m far away from the platform are comprised in the model and ends of the tunnel are set as pressure boundaries with the same value as out-door pressure.
Smoke exhaust and air supply inlets: flow-out speed or flow-in speed are given to them.
Shutter: Shutters are set as baffle boundaries. Opening and closing of the shutters are reproduced by setting the baffle boundaries as transparent or in-transparent.

(2) Fire source
In the experiments ethanol is used as fire source, however, fire source is reproduced by heat flux walls with 500 mm × 500 mm, 6 spots near the stairs are considered as fire source in this simulation. Heat flux from fire source is entirely dissipated to convection in this simulation, radiation influence is neglected.

(3) Experimental conditions for simulation
The 3 following conditions are used to reproduce the experiments using CFD.

- Shutters: Closed, Platform smoke extraction fan: OFF
- Shutters: Closed, Platform smoke extraction fan: ON
- Shutters: Open, Platform smoke extraction fan: ON

Fire source: 480 kW (500 mm × 500 mm：80 kW at 6 spots)
Capacity of Smoke extraction fan of the platform: 132,552 m^3/h

(4) CFD calculation results (Fig. 2, Fig. 3)
CFD calculation and experimental results are shown in Fig. 2. The results of two-zone model are also listed for reference [2]. The CFD calculation results are approximately agreed with the experimental results but the results of the Two-zone model can not reproduce the temperature distribution with the shutter open (Fig. 2 (c)).

Temperature distribution from the stairs to the fire source is also reproduced in the calculation results when plume is diluted with the shutter open. Therefore the CFD model is thought to be effective to predict the smoke movement character in case of a subway fire.

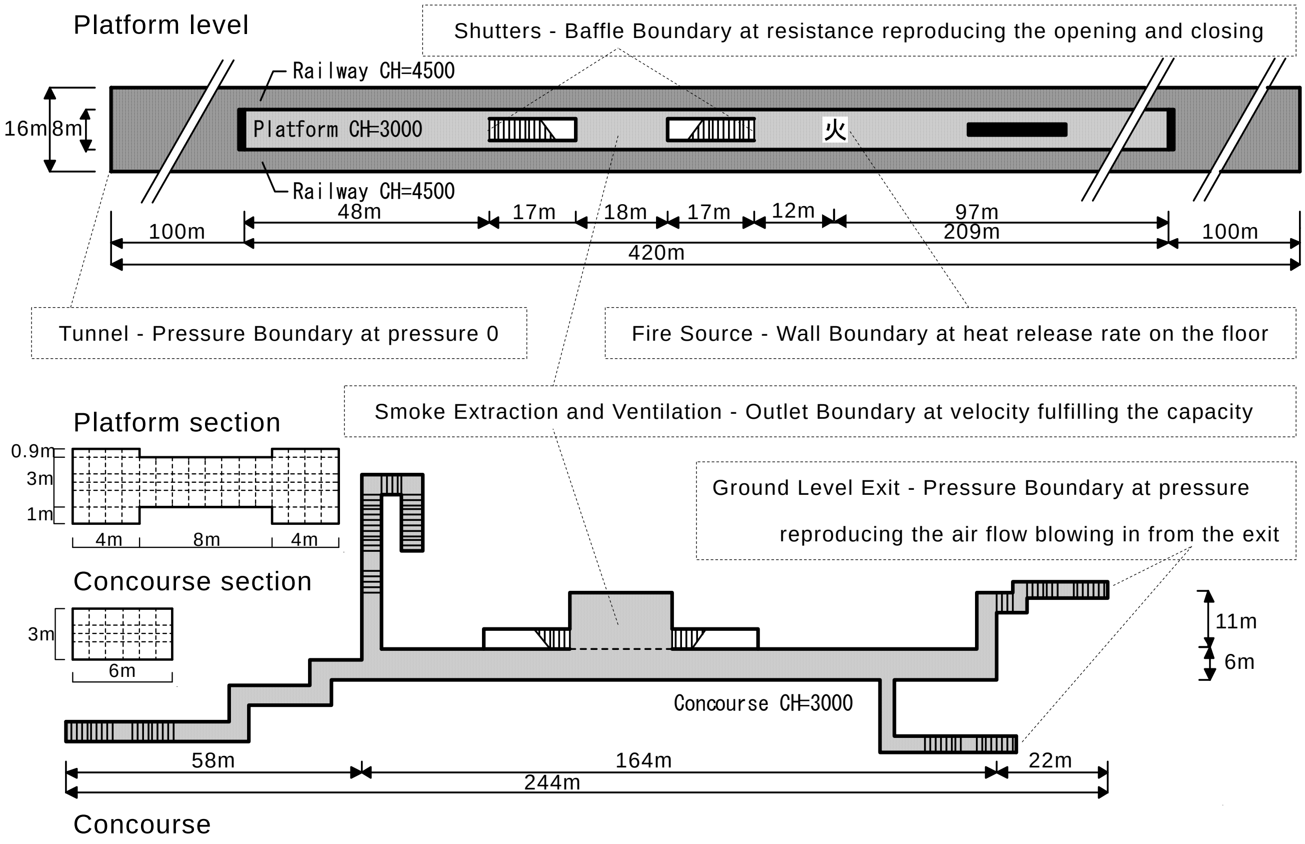

FIGURE 1. Plan of the subway station and boundary conditions

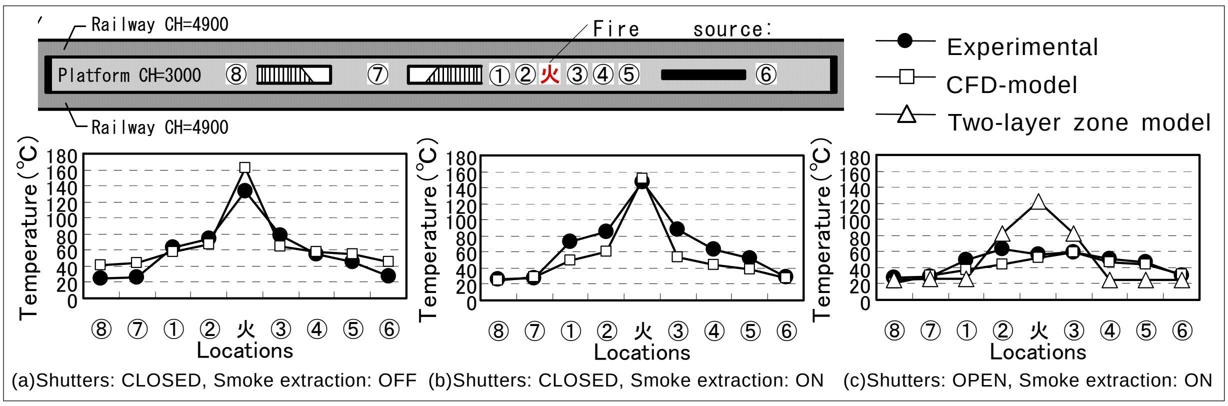

FIGURE 2. Experimental and numerical temperatures

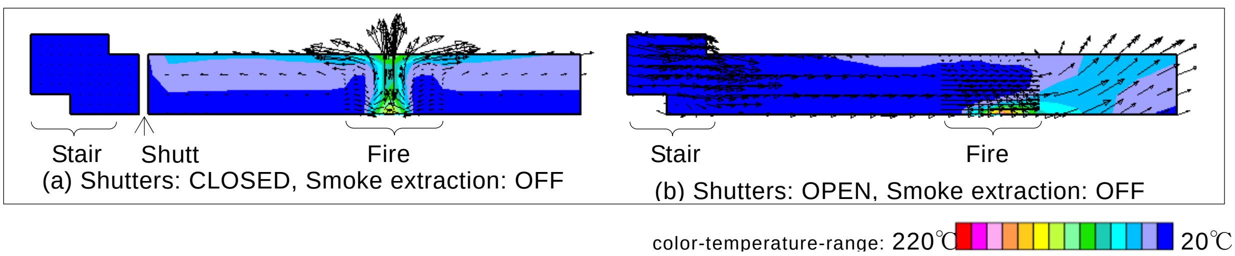

FIGURE 3. CFD model simulation cross section temperature

EVACUATION SAFETY OF A CENTER PLATFORM STATION

Considering a fire source as 10 MW such as a shop or a single train compartment fire [5], the above CFD model is used to discuss the safety of the existing smoke control system when a fire occurs on the center platform. Evacuation simulation is calculated to get the times to clear the platform and concourse. CFD calculation results at the times to clear the platform and concourse are used to evaluate the smoke control systems. And furthermore proper smoke control system for the center platform will be discussed.

(1) Evacuation simulation

Evacuation simulation is calculated based on Notification No. 1441 and No. 1442 designated by Japanese Ministry of Land, Infrastructure and Transportation (MLIT). The door width of the stairs, through which evacuees on the platform pass to the concourse, is the most important factor affecting the evacuation time. Three conditions, case 1 (2 shutters are open), case 2 (1 shutter open and 1 emergency door open) and case 3 (2 shutters closed and 2 emergency doors open), are calculated (Table 2 *2). The results are listed in Table 2. It is clear that time to pass the evacuation door has a greater effect than traveling time. Time to clear the platform of case 1 is 5 minutes (including time to pass the evacuation door: 4 minutes), for case 2 is 7 minutes (including time to pass the evacuation door: 6 minutes) and for case 3 is 15 minutes (including time to pass the evacuation door: 14 minutes). Results with shutter open or closed are quite different. Time to clear the concourse (inside of paid area) is 13 min for case 1 and 2, and 16 min for case 3. Time to clear the subway station is 16 min for case 1 and case 2, and 19 min for case 3. Time to clear the paid area of case 1 and case 2 is the same. It is because the ticket gate width is narrow and time to pass the ticket gate almost decides the time to clear the subway station of case 1 and case 2.

(2) CFD calculation

Temperature distribution of the platform at the time to clear the platform, temperature distribution of concourse at the time to clear the paid area, and temperature distribution at the time to clear the subway station are calculated by CFD. Growing rate of the fire source is considered as 0.246 kW/s^2 with 100% convection dissipation. Generally 30% of the fire source heat is dissipated through radiation. Therefore calculated smoke temperature will be higher than general conditions.

(3) Safety of existing smoke control system (Figs. 4 and 5)

Performance of existing smoke control system (platform smoke extraction and concourse smoke extraction) is discussed with a fire source of 10 MW. The capacity of smoke extraction fan of the center platform actually in service is 132,552 m^3/h, and capacity of smoke extraction fan of the concourse is 144,316 m^3/h. There are 84 smoke vents on the platform ceiling and 41 on the concourse ceiling with the size of 1000mm×1000mm. In the CFD calculation, smoke vents are set as outlets. Smoke vents are open at the time to start evacuation. It is considered smoke extraction fan takes 1 minute to reach full capacity. Shutters which connected the platform and the concourse are all set as open. Temperature at FL+2.5 m of 200 degree C (sufferable radiation from smoke layer, see “NOTE”) and temperature at FL+1.8 m of 40 degree C is used to assess safety. When evacuation time is over the critical exposed time, it is thought evacuee is not safe and furthermore detail discussion is necessary.

TABLE 2. Result of evacuation simulations

Spaces	Items	Equations for calculation of evacuation times			Case1	Case2	Case3	Remarks
Platform (B2F level)	Platform Area	A_h	(m²)		1,352			
	Occupants in the platform	P_h	(persons)	$(P_c \times N_c + P_t) \times R_p/100$	2,588			*1
	Total width of evacuation route	ΣW_h	(m)		8.00	5.05	2.10	*2
	Time to pass the evacuation doors	t_{hq}	(min)	$P_h/(N_p \times \Sigma W_h)$	3.6	5.7	13.7	
	Traveling distance of longest exit route	L_h	(m)		113			
	Traveling time in the platform	t_{ht}	(min)	L_h/v	1.9			
Stairs from Platform to Concourse	Traveling distance of stairs to the concourse	L_{hs}	(m)		16			
	Travelin time going up stairs	t_{st}	(min)	L_{hs}/v_s	0.6			
Paid Area (Concourse, B1F level)	Occupants in the Paid Area	P_{ci}	(persons)	$P_t \times 0.5$	54			*3
	Occupants passing through the Paid Area	P_{h+ci}	(persons)	$P_h + P_{ci}$	2,642			
	Total width of evacuation route	ΣW_{ci}	(m)		2.80			*4
	Time to pass the evacuation doors	t_{ciq}	(min)	$P_{h+ci}/(N_p \times \Sigma W_{ci})$	10.5			
	Traveling distance of longest exit route	L_{ci}	(m)		21			
	Traveling time in the Paid Area	t_{cit}	(min)	L_{ci}/v	0.4			
Free Area (Concourse, B1F level)	Occupants in the Free Area	P_{co}	(persons)	$P_t \times 0.5$	54			*5
	Occupants passing through the Free Area	$P_{h+ci+co}$	(persons)	$P_h + P_{ci} + P_{co}$	2,696			
	Total width of evacuation route	ΣW_{co}	(m)		15			
	Time to pass the evacuation doors	t_{coq}	(min)	$P_{h+ci+co}/(N_p \times \Sigma W_{co})$	2.0			
	Traveling distance of longest exit route	L_{co}	(m)		139			
	Traveling distance of stairs to the outside	L_{cos}	(m)		28			
	Traveling time in the Free Area	t_{cot}	(min)	$L_{co}/v + L_{cos}/v_s$	3.4			
Results of Evacuation simulation (After Ignition)	Time to start evacuation in the Platform	T_{sh}	(min)	$\sqrt{A_h}/30$	1.2	1.2	1.2	
	Time to clear the platform	T_{eh}	(min)	$T_{sh}+max(t_{hq},t_{ht})$	4.8	6.9	14.9	*8
	Time to start evacuation in the Paid Area	T_{sci}	(min)	$T_{sh}+t_{st}+t_{cit}$	2.2	2.2	2.2	*6
	Time to clear the Paid Area	T_{eci}	(min)	$MAX(T_{sci}+t_{ciq}, T_{eh}+t_{st}+t_{cit})$	12.7	12.7	15.9	*8
	Time to start evacuation in the Free Area	T_{sco}	(min)	$T_{sh}+t_{st}+t_{cit}+t_{cot}$	5.5	5.5	5.5	*7
	Time to clear the Free Area	T_{eco}	(min)	$MAX(T_{sco}+t_{coq}, T_{eci}+t_{cot})$	16.0	16.0	19.2	*8
Characteritic common items	Traveling speed(Horizontal)	v	(m/min)		60			
	Traveling speed(Stairway, upward)	v_s	(m/min)		27			
	Flow rate through the evacuation door	N_p	(persons/(min・m))		90			
	Averaged occupants getting on & off per train	P_t	(persons/train)		108			*1
	Quota of a car	P_c	(persons/car)		153			*1
	Number of cars in a train	N_c	(cars)		10			*1
	Ratio of overload for the quota of a car	R_p	(%)		158			*1

*1 Reference 6)
*2 Case1: 2 shutters (Width=4m, each) between Platform & Concourse are full-open
Case2: 1 shutter (Width=4m) between Platform & Concourse is open, 1 evacuation door (Width=1.05m) for the closed stair is open
Case3: All shutters are closed, 2 evacuation doors (Width=1.05m, each) for the closed stairs are open
*3 It is assumed that half of occupants who are going to get on the next train and had got off the last train exist in the Paid Area
*4 Total width of ticket barrier (0.7m × 4)
*5 It is assumed that half of occupants who are going to get on the next train and had got off the last train exist in the Free Area
*6 Time for the nearest person to the escape stair on the platform, first evacuee from the platform, to reach the exit to the Free Area
*7 Time for the nearest person to the escape stair on the platform, first evacuee from the platform, to reach the exit to the outside of the station
*8 Reference 4)

Temperature distribution of section from H1 to H7, from C1 to C5 is shown in Fig. 4 with smoke vents of platform open or closed, and smoke vents of concourse open or closed.

Temperature at 1.8 m and 2.5 m above the floor is shown in Fig. 5. Upper space of the tunnel works as smoke accumulation space and has a great effect on the calculation results. High temperature (from 200 to 350 degree C) smoke spread throughout upper space of the platform. In Fig. 5, temperature at FL+1.8 m near the fire source is lower than that far away from the fire source. It is thought high temperature smoke near the fire source spread through upper space of the tunnel and flow into the lower space mixed with atmosphere far away from the fire source. In Fig. 4, contour line of 40 degree C descends lower near the fire source than that far away (H1, H7). In Fig. 5 (a), without smoke extraction (case 1), temperature near the fire source exceeds allowable value of 200 degree C. Stairs near H4 can not be used and evacuee at H6 and H7 will have no evacuation route.

With smoke extraction fan ON in the platform (case 2), temperature of the concourse is lower than that without smoke extraction fan (case 1). However, temperature at FL+1.8 m exceeds 40 degree C. From Fig. 5(b) and Fig. 5(d), it is known when there is no smoke extraction in concourse, temperature at C1, C2, C3 ascend obviously comparing with C4 and C5.

With smoke extraction fan ON in the concourse (case3), temperature at C1, C2 and C2 almost have no change, and at C4, C5, temperature becomes 10 Kelvin higher comparing with case 2. It is considered smoke is pulled up from platform to C4 and C5 by the smoke extraction fan. As the results, temperature of the concourse at FL+1.8 exceeds 40 degree C. Therefore, smoke extraction at concourse does not always make the temperature of concourse lower; adversely it is possible to make the temperature of concourse become higher.

In case of a 10 MW fire, the existing smoke control system cannot ensure evacuation safety of the station, it is necessary to make detailed discussion.

IMPROVED METHOD FOR EVACUATION SAFETY OF THE STATION

From Figs. 7 to 10 show temperature results of several measures used to improve the fire safety performance. Smoke extraction system or pressurized system works at the time to start evacuation. It is considered fans of smoke control systems take 1 minute to reach full capacity. Shutters near and far from the fire source are all open except Fig. 10.

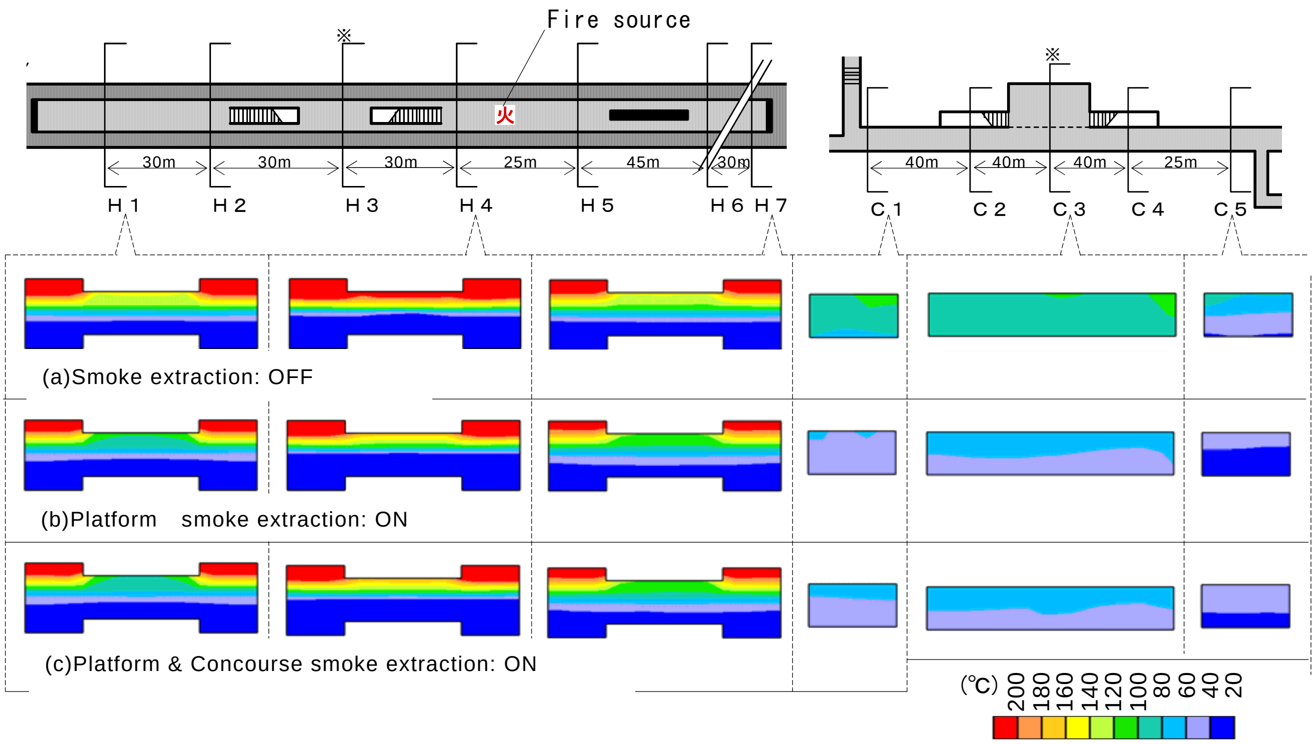

FIGURE 4. Visualized temperature in section (H1, H4, H7: 5 min, C3: 13 min, C1, C5: 16 min after ignition)

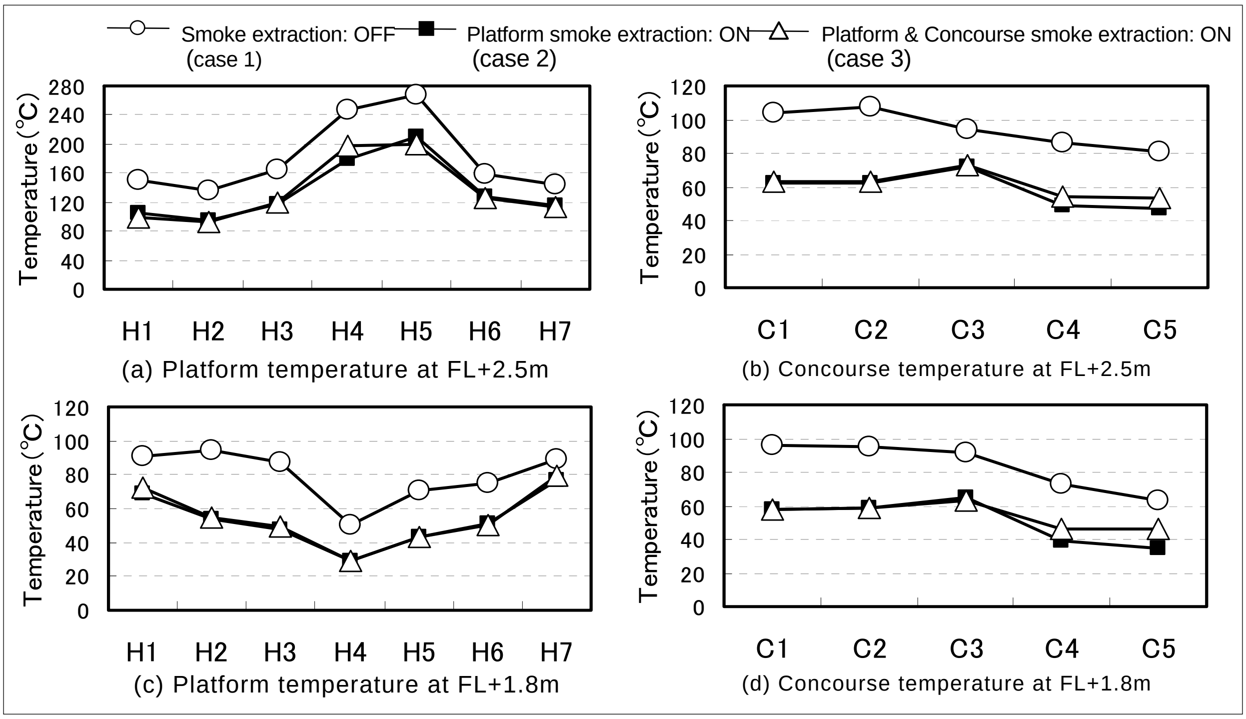

FIGURE 5. Platform and concourse temperature (H1-H7: 5 min, C3: 13 min, C1, C2, C4, C5: 16 min after ignition)

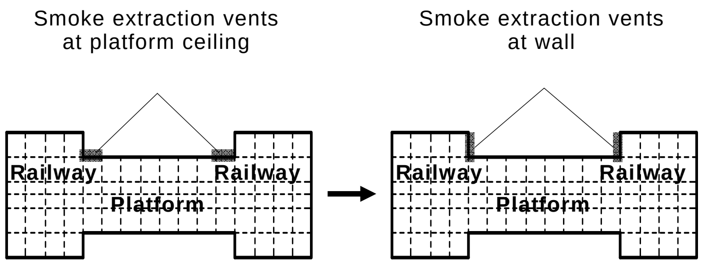

FIGURE 6. Smoke extraction position in platform section

(1) Strengthen smoke extraction capacity of the platform (Fig. 7, case 4)
When smoke extraction capacity of the platform becomes 2 times of existing system as 265,10 m^3/h (case 4), temperature at FL+2.5 becomes from 15 to 50 Kelvin lower comparing with case 2. Especially temperature at H5 descends obviously and lower than the allowable value of 200 degree C for evacuation. Although temperatures at FL+1.8 m descend from 5 to 15 Kelvin, it is still over 40 degree C. In concourse, temperatures at FL+2.5m descend 10 Kelvin at C4 and C5, and temperatures at FL+1.8m descend 10 Kelvin at C3 comparing with case 2. As in the platform, at FL+1.8 m temperature still exceeds 40^{o}C.

(2) Change location of the smoke vents of platform (Fig. 7, case 5)
Improving location of smoke vents are moved to side upper space of tunnel from the surface of ceiling (case 5) as shown in Fig. 6. Along the tunnel, 84 smoke vents are set as outlets with size of 1000 mm × 900 mm. Smoke extraction fan capacity keeps the same as 132,552 m^3/h.

Comparing with existing system with smoke extraction fan in operation (case 2), temperature of improving system descends obviously far from the fire source on the platform. At Fl+2.5m temperatures at H1, H2, H6, H7 of improving system descend from 30 to 40 Kelvin and at FL+1.8 m temperatures descend from 10 to 20 Kelvin comparing with case 2. Smoke vents in the side upper space of tunnel prevent high temperature smoke spread to platform. However temperature at Fl+1.8 m of the platform is still over 40 degree C. Temperature in the concourse shows no descent.

(3) Strengthen smoke extraction capacity of platform and change location of smoke vents (Fig. 7, case 6)
Smoke extraction capacity of platform is set as 2 times of existing system as 265,104 m^3/h and smoke vents is allocated in the side upper space of tunnel (case 6). Comparing with the existing system (case 2), at FL+2.5 m temperatures in the platform of improving system descend from 30 to 70 Kelvin, at FL+1.8 m temperatures descend from 5 to 50 Kelvin. Temperatures in the platform at FL+1.8 m of improving system become lower than 40 degree C. In the concourse, 10 Kelvin descent is obtained comparing with case2 while at FL+1.8 m temperatures at C1, C2, C3 are still over 40 degree C.

(4) Strengthen smoke extraction capacity of concourse (Fig. 8, case 7)
Smoke extraction capacity of the concourse is set as 2 times of existing system as 288,632 m^3/h (case 7). Comparing with smoke extraction fan OFF (case 2), temperatures at FL+1.8 m in the concourse become lower, however, they are still over 40 degree C.

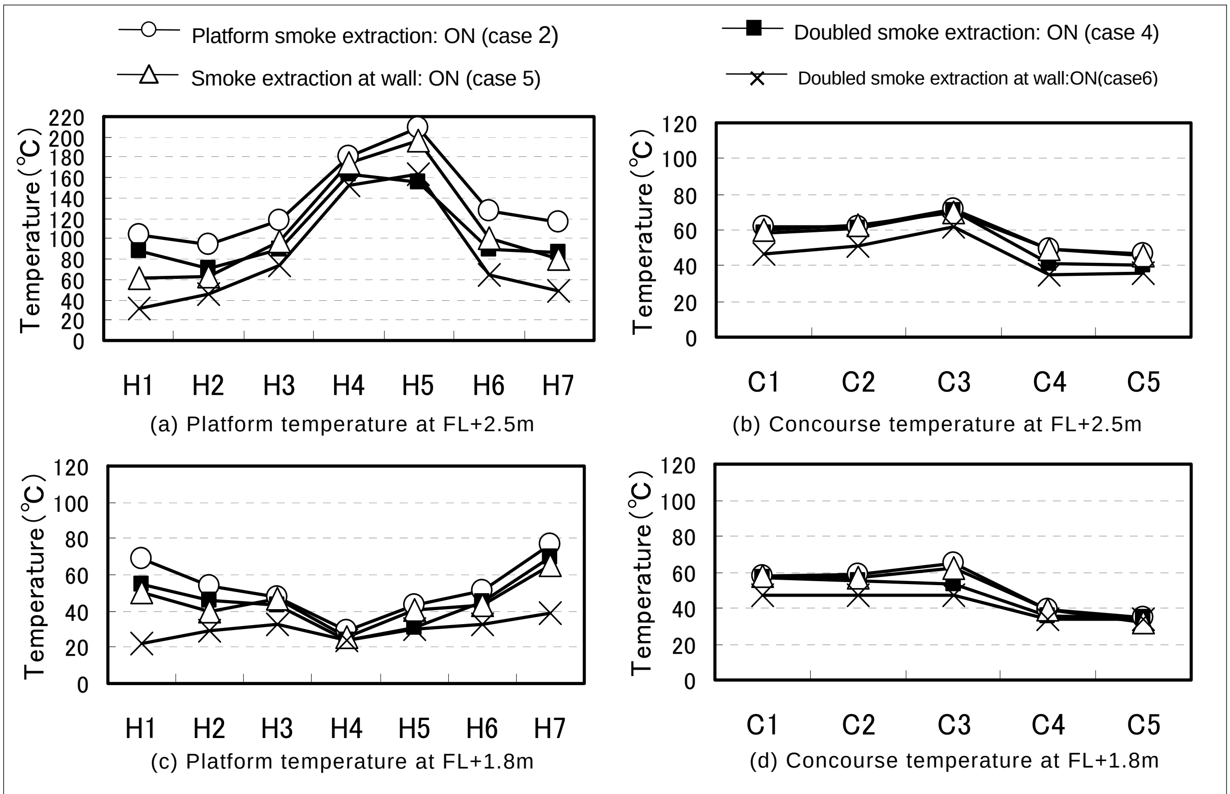

FIGURE 7. Effects of platform smoke extraction (H1-H7: 5 min, C3: 13 min, C1, C2, C4, C5: 16 min after ignition)

(5) Supply air to the concourse (Fig. 9, cases 8 and 9)
Air supply capacity to the concourse is supposed as 144,316 m^3/h (case 8). Air supply vents on the ceiling of concourse is set as inlets with size of 1000 mm × 1000 mm. At FL+1.8 m temperatures at C1, C2 and C3 become from 10 to 20 Kelvin lower, while temperatures at C4 and C5 become 15 Kelvin higher comparing with case2. It is thought smoke layer is disturbed by supply air from the ceiling. Even by setting air supply volume as 288,632 m^3/h (case 9), temperatures at C4 and C5 keep 10 Kelvin higher comparing with case 2. Therefore, air supply lower than 288,632 m^3/h does not necessarily make the temperatures of the concourse descent.

(6) Operation of the shutters (Fig. 10)
There are two shutters which connected the platform and the concourse on the platform, one is near the fire source and another is far from the fire source. The following 3 actions are taken with existing smoke extraction fan ON. At the time fire occurs, two shutters are completely open and 1 minute later actions are taken to operate the shutters.

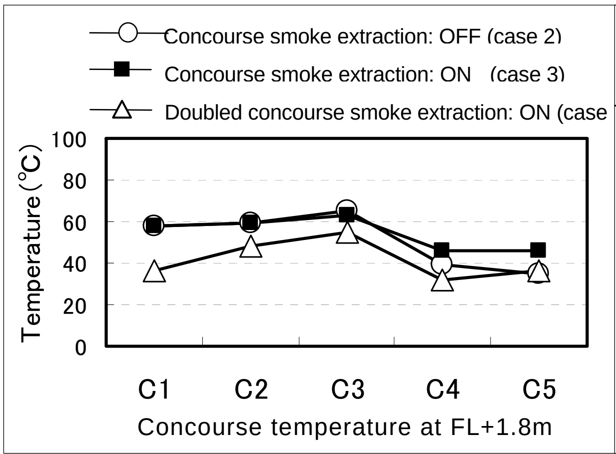

FIGURE 8. Influence of concourse smoke extraction (C3: 13 min, C1, C2, C4, C5: 16 min after ignition)

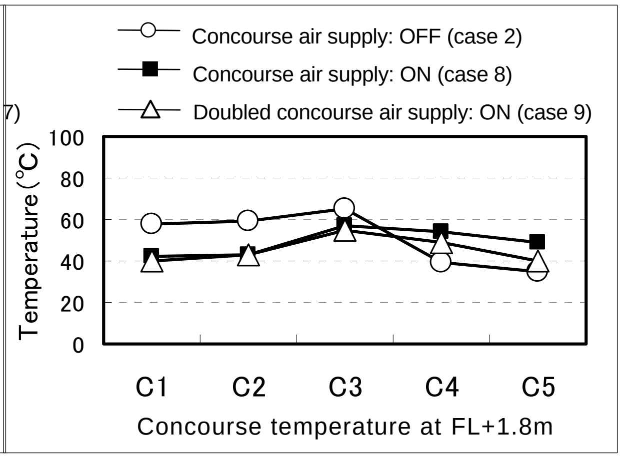

FIGURE 9. Influence of concourse air supply (C3: 13 min, C1, C2, C4, C5: 16 min after ignition)

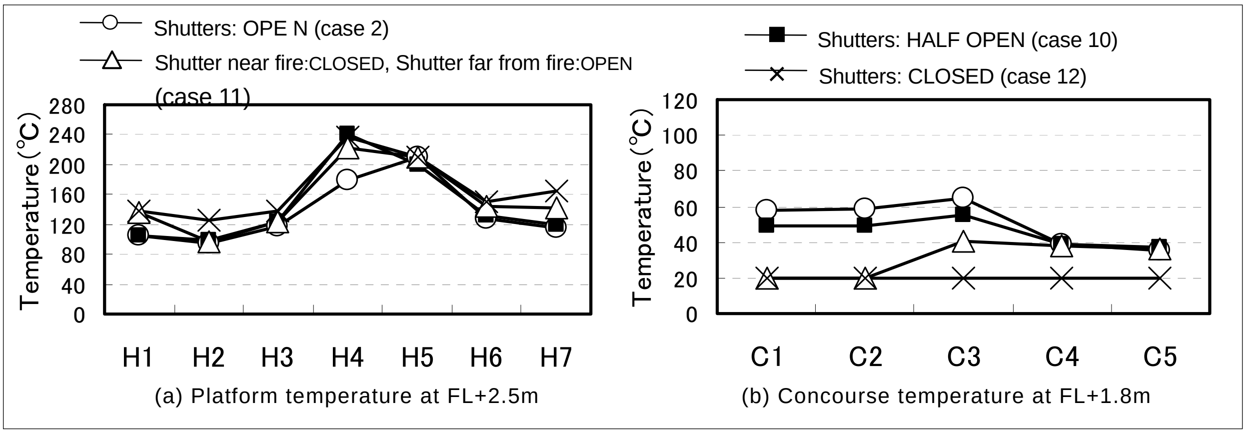

FIGURE 10. Influence of shutter operation
Shutters: OPEN & Shutters: HALF OPEN (H1-H7: 5 min, C3: 13 min, C1, C2, C4, C5: 16 min after ignition)
Shutter near fire: CLOSED, Shutter far from fire: OPEN (H1-H7: 7 min, C3: 13 min, C1, C2, C4, C5: 16 min after ignition)
Shutters: CLOSED (H1-H7: 15 min, C3: 16 min, C1, C2, C4, C5: 19 min after ignition)

- **Half open** (Fig. 10, case10)

Set the bottom edge of the shutters down to the position of 1 m below the ceiling (case 10). Evacuee can go to the stairs through lower open part of the shutter. Time to clear the platform is set as the same as when two shutters are all open.

Comparing with shutters full-open (case 2), temperatures at FL+1.8 of the concourse at C1, C2, and C3 descend about 10 Kelvin, however, those remain over 40 degree C. In the platform, temperature at H4 in front of the shutter rises obviously and becomes over the allowable value of 200 degree C. With the shutter half open, temperatures ascent in the concourse is prevented in some degree, however, temperature at H4 in front of the shutter becomes higher.

- **Shutter near the fire source closed** (Fig. 10, case 11)

Comparing with shutter half open (case 10), temperature ascent in the concourse is prevented further. Especially, temperatures at FL+1.8m at C1 and C2 hardly change, all of the area keeps below 40 degree C except C3. In the platform, not only location of H4, temperatures in all area reveal ascent. At H1 and H7, the ends of the platform, temperature ascends 30 Kelvin comparing with shutter full-open (case 2). It is clear that smoke spread to the concourse is prevented with the shutter near the fire source with closed, however, more of the area of platform is polluted by the smoke.

- **Shutter near the fire source and shutter far from the fire source both closed** (Fig. 10, case 12)

Temperature rise in the concourse is not observed. In the platform, comparing with only shutter near the fire source closed (case 11), temperature is higher. Smoke spread to the concourse is completely prevented, however, smoke spread to larger space in the platform.

(7) Restrain of the fire source (Fig. 11, cases 13, 14 and 15)

On the premise of existing smoke extraction in the platform, assuming the fire source as 10 MW (case 2), 5 MW (case 13), 3 MW (case 14) and 2 MW (case 15) respectively, temperature changes in the subway station are compared. As long as the fire source is below 5MW, no area is observed over 200 degree C at FL+2.5m (Maximum value: 130 degree C at H4). At FL+1.8 m with fire source of 5 MW (case 13), temperatures in the platform at H1, H2, H3, H7, and temperatures in the concourse at C1, C2 and C3 are over 40 degree C. With the fire source of 3 MW (case 14), temperature in the platform at H7 is over 40 degree C, however, temperature over 40 degree C is not observed in other area. With the fire source of 2MW (case 15), all the area in the platform and concourse is below 40 degree C.

(8) Reduction of the evacuation time

The following methods can be considered to reduce evacuation time when the subway station is in confusion at ticket gate.

1) Adding the emergency stairs from the platform to concourse. Especially installation of stairs to outside directly passing through the ticket gate will greatly reduce confusion condition at ticket gate of the concourse.
2) Increase width or numbers of ticket gate. Specifically it is effective to increase one ticket gate in addition to existing 4 ticket gates of 0.7 m width, 5 ticket gates in total.

If taking the method of 1) or 2), time to clear the platform of Case 2 in Table 2 can be reduced by 1.6 minutes (6.9 min to 5.3 min), time to clear the paid area can be reduced by 4.5 minutes (12.7 min to 8.2 min）, time to clear the station can be reduced by 4.5 minutes (16.0 min to 11.5 min).

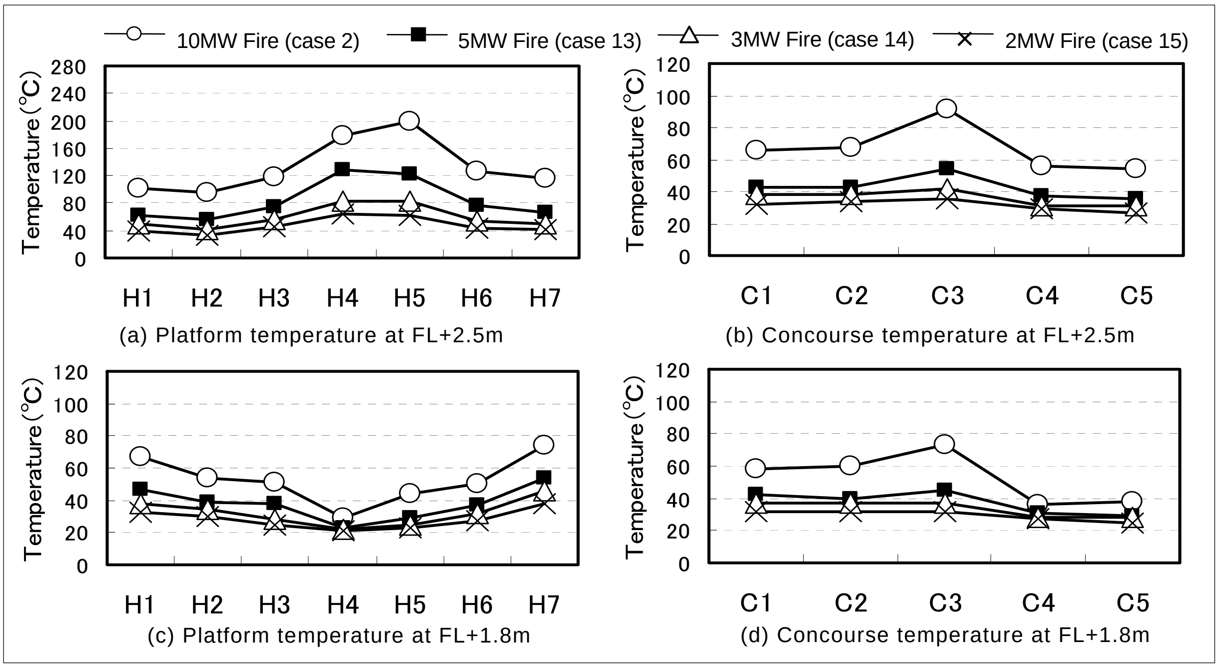

FIGURE 11. Influence of fire source intensity (H1-H7: 5 min, C3: 13 min, C1, C2, C4, C5: 16 min after ignition)

CONCLUSION

CFD calculation is performed to predict smoke movement in subway station. The following results can be obtained.

(1) Smoke movement occurring in the experiment at the supposition of an early stage of fire cannot be completely reproduced by two-zone model with shutter open, but it can be well reproduced by CFD calculation.
(2) Safety of the platform can be improved by increasing smoke extraction capacity or arrangement of smoke vent in some degree, however, it is the most important to restrain fire source by using noncombustible materials for interior finishing of the station.
(3) With shutters half open or fully closed, smoke spread to the concourse can be prevented and concourse safety is proved. However, temperature in the platform rises obviously and safety of the platform may become worse.
(4) Adding the emergency stairs, especially ends of a platform, can ensure alternative evacuation routes of a platform. At the same time, it makes evacuation time reduced greatly.

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NOTES

When smoke below the ceiling is 200 degree C and emissivity becomes 1.0, evacuee under the ceiling will be exposed to radiation heat of 2.84 kW/m^2. Allowable exposure time is only several minutes [9]. Smoke temperature around 200 degree C may cause melt and drop of lighting appliance.

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