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A study of Heat & Smoke Extraction Effects by the Various Operation of Tunnel Fan Shaft Ventilation

터널팬 샤프트 환기 방식에 따른 열 및 연기배출효과에 관한 연구

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요 약

지하철은 다른 구조물과 비교하여 화재발생시 화재진압 및 인명구조에 본질적으로 취약한 구조적 특성을 내포하고 있다. 국내의 경우, 지하철 승강장 제연설비는 전용설비로 구축되어 있지 않고 화재발생시 승강장환기설비 및 본선터널부의 환기설비를 제연모드로 절환하여 운영되고 있다. 제연효과는 이러한 까닭으로 환기설비의 위치, 용량 및 급배기방식에 종속된다. 본 연구에서는 지하철 승강장에서 열차 화재 발생시, 승객의 안전한 대피로 확보가 가능한 선로부 환기기의 제연운전효과의 실효성에 대한 검증을 목표로 한다. 따라서 지하승강장을 대상으로 승강장내 기류해석 및 3차원 화재시뮬레이션을 수행하여 열차화재에 따른 승강장내 열 및 물질이동특성해석으로부터 선로부 배연운전모드에 따른 특성을 규명함으로서 승객 안전성 확보에 목표를 둔다.

ABSTRACT

Today's popular ventilation systems include the combined jet fans and electrostatic precipitation systems or the combined jet fans and vertical shaft system. Tunnels with these two ventilation systems applied have been designed and opened, more and more interest has been put in maintenance of a tunnel after opening. Therefore, it is to become more important to come up with the optimal operation mode and the method for the evaluation of ventilation system. In this study, to evaluate a tunnel ventilation and its economy, a dynamic simulation program was developed which can simulate the unsteady-state tunnel air velocity and concentration of pollutants according to the traffic flow variations and operation condition of a ventilation system. We clarified the effectiveness usage on tunnel ventilation by using it and also we could found the most economical ventilation operation mode by application in real exit tunnel. We obtained that combination of fan system and electrostatic precipitation system was more economical than jet fan priority operation mode.

Keywords : Smoke exhaust, Ventilation system, Subway station fire, Evacuation

1. Introduction

Breakout of fire in underground facilities has high tendency to escalate into major disasters for the fact that it normally takes place in semi-enclosed spaces as evidenced during the Daegu subway line tragedy a few months back. Fire prevention studies so far have focused on making preparations within the range of normal fire occurrences; however, fire events are now heading in the direction of including deliberate incidents caused by the likes of terrorism and such as a global effort.[1] And the necessity of applying fire protection to underground spaces has been further acknowledged since the wake-up call of the Daegu subway line tragedy. Subway is a typical structure that carries an inherent characteristic of providing poor conditions to fight fire and rescue victims, and there are approximately 300 km of subway lines in Seoul, Incheon, Busan, and Daegu: a

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figure expected to reach 600 km by 2005. This study therefore aims to derive a comprehensive ventilation system operation method capable of providing passengers with safe exit paths from platforms in on board fire situations. To accomplish this, airflow distributions in subway platforms under normal conditions were calculated in addition to having analyzed diffusion behaviors of smoke and heat exhaust characteristics in such states by performing fire scenarios in a 3-D simulation model. Consequently, a safe passenger evacuation program was devised after having examined exhaust gas characteristics in each tunnel smoke exhaust modes.

2. Platform Fire Analysis

Research into fire in subway stations that depend on structural formations that agree with corresponding geographical characteristics, platform conditions, and operating modes of smoke ventilation facilities, have been applied as a part of disaster prevention.[2,4]

Taking South Korea as an example, platform smoke ventilation facilities are not currently installed as standard equipments, and platform ventilation facilities and tunnel ventilation systems are set to convert to smoke ventilation mode when fire is detected. For such reasons, heat exhaust effect has shown a tendency to depend on the location of ventilation facilities and method of supply and exhaust. In this study, analysis of smoke exhaust characteristics that included ventilations in platform and tunnel areas was performed on the basis of the following:

(1) Passenger Evacuation Time Assessment: Utilizing SIMULEX,[5] passenger evacuation times in cases of fire breakout in a stopped train car were yielded. Degree of smoke concentration that took its exposure time into consideration was examined based on the calculated times.

(2) Analysis of Airflow under Ventilation Facility Operation Modes: SES (Subway Environmental Simulation)[6] was utilized to analyze platform area's airflow formed by ventilation facility's conversion to exhaust operation to apply the findings as boundary conditions of fire simulations.

(3) Fire Intensity Assessment: Assessed the heat release rate during subway fire. Under the current situation where no detailed document pertaining to heat release rate in South Korean subway cars are available, in this study has adopted for documents from NFPA[7] to assess fire intensity.

(4) Assessment of Standards Pertaining to Safe Evacuation Temperature and Visibility during Evacuation: Whether density of smoke and temperature distribution generated during the course of evacuation can be maintained within the limits of evaluation allowances or not is determined.

(5) 3D Platform Airflow and Smoke Propagation Analysis: Unsteady state analysis was performed through FDS (Fire Dynamic Simulation)[8] utilizing platform airflow, temperature and smoke concentration analysis.

(6) For the purpose of establishing the most optimal smoke exhaust mode during fire, comparative analysis of smoke concentration and temperature distributions were performed by each operating mode of tunnel fan shaft ventilation facilities so that the most appropriate mode in evacuation could be derived.

2.1 Evacuation Time Assessment

Table 1 shows the platform specifications of the analysis model applied to this study.

The subway train applied in the evacuation simulation was set to be 8 cars long with maximum 990 passengers; hence, 123 to 125 passengers were set per each train

Table 1. Platform specifications of the analysis mode

Classification		Dimension (m)	Etc.
Subway station	Height of Floor	1.6	Side-platform station
	Height of ceiling	3	-
	Length	185	-
	Width of station	4	-
Rail road track	Cross section area	41.04 (W7.6×H5.4)	2 railway
Train	Width	2.75	-
	Height	3	-
	Height of air conditioner	0.5	-
	Length of train	144.5 (18 m/vehicle)	8 train vehicles

Table 2. Composition of passengers per each case

Car	Male	Female	Child	Total
1st	50	50	24	124
2nd	49	49	25	123
3rd	50	50	25	128
4th	49	49	25	127
5th	49	49	25	128
6th	49	49	25	129
7th	50	50	24	131
8th	50	50	25	125

Table 3. Fire occurring condition

Case	Conditions	
	Location of Fire generated	Door operation mode
1	1st train vehicle	close
2	5th train vehicle	close
3	5th train vehicle	open

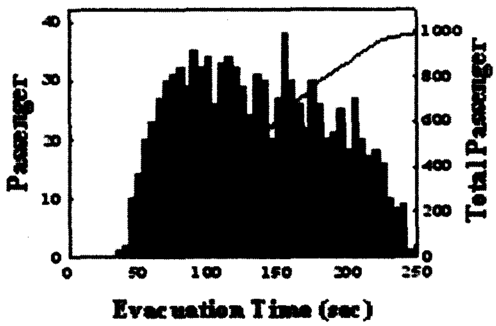

Fig. 1. Evacuation time for case 1.

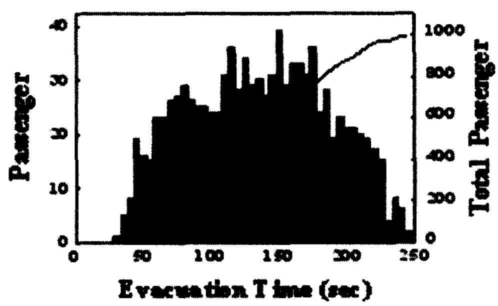

Fig. 2. Evacuation time for case 2.

car. Passenger ratio was arranged at 40% males, 40% females, and 20% children (sex irrelevant). Composition of passengers per each car is shown in Table 2, and fire

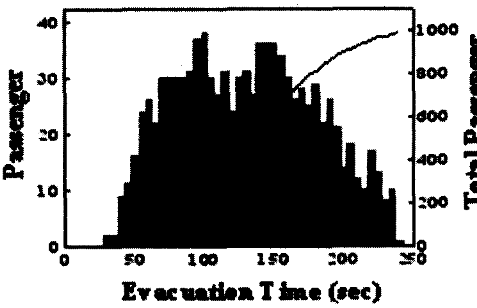

Fig. 3. Evacuation time for case 3.

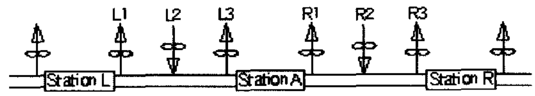

Fig. 4. Location of up and down line tunnel fan shaft array from model station.

occurring conditions are as indicated in Table 3.

Figs. 1 to 3 each show results under the conditions of cases 1 to 3, and it was found that passengers were able to evacuate within 240 to 250 seconds when fire broke out, depending on changes to exit door opening and closing conditions.

2.2 Airflow Analysis in Accordance to Tunnel Fan Shaft Operating Mode

Airflow in platform areas is influenced by operation modes of tunnel vent system and platform ventilation systems. Consequently, a model that included both up and down lines around the station model was constructed and the SES (Subway Environmental Simulation) program was utilized to analyze airflow. The section was formed as a single route, and calculations were made to include both up and down lines as a single section so that accuracy would be raised. Therefore, subway environment analysis was formed in 7 zones, 59 line sections, and 12 upper and lower track exhaust system stairs and platform-vent sections. Fig. 4 shows location of up and down line tunnel fan shaft array from model station 'A' having set use of the ventilation fan shaft as a constant, the following three smoke exhaust modes were configured by the changing operating mode of tunnel fan shaft ventilation:

(1) Configuring Normal Ventilation

Mode to Smoke Exhaust Mode: Operation of tunnel fan shaft ventilation at up and down line tunnel during fire in an identical manner to normal ventilation mode (smoke exhaust mode: L1, L3, R1, R3 supply fresh air mode: L2, R2).

(2) Configuring All Tunnel Fan Shaft Ventilation to Smoke Exhaust Mode: Letting all ventilation fans in the tunnel to exhaust (L1, L2, L3, R1, R2, R3).

(3) Configuring Push-Pull mode to Smoke Exhast Mode: Unidirectional airflow within a station by setting mode at one side of the tunnel as supply (L1, L2, L3) and on the opposite side of tunnel as smoke exhaust (R1, R2, R3).

In all the above three conditions, track exhaust system was configured smoke exhaust mode in both up and down areas.

2.2.1 Air Volume When Configuring Normal Ventilation Mode to Exhaust Mode

In-flowing air volume at the up line (from the station L) was measured at approximately 450 m^3/min and air volume out-flowing at the down line (to the station R) was measured at approximately 109 m^3/min and thus, both in-flowing and out-flowing air volumes were found to be small enough to discard.

Direction of the main current in the platform area was found that open air was in-flowing through the stair way and being ventilated (4215 m^3/min) via the platform area's ventilation system. The total amount of air volume that in-flowed through the stairways was measured at approximately 3870 m^3/min and was entirely ventilated by TES.

2.2.2 Air Volume When Configuring All Tunnel Fan Shaft Ventilation to Smoke Exhaust Mode

Centered on the station 'A', this is a case where down line tunnel shaft fans (110, 111, 112) and up line tunnel shaft fans (119, 120, 121) are all operated in smoke exhaust mode. Since smoke is ventilated in both directions around the case station, about 17548 m^3/min of fresh air in-flowed through the stairways. In-flowed air is almost evenly distributed in both directions (from the platform to the up line tunnel: 6220 m^3/min vs. from the platform to the down line tunnel: 7128 m^3/min), and exhaust volume of TES showed to be at a value of 4197 m^3/min.

2.2.3 Air Volume When Configuring Push-pull mode to Smoke Exhaust Mode

The direction of the main air flow in the platform area is formed from the up line (from the up line tunnel to the platform: 7512.3 m^3/min) to the down line direction (from the platform to the down line tunnel: 11097.1 m^3/min), fresh air inflows through the stairways, air volume (7804 m^3/min) showed a decreased in comparison to the all smoke exhaust mode method, and a large inflow volume (7803.9 m^3/min) was detected. Smoke exhaust rate over the platform area was 4220 m^3/min.

2.3 Heat Release Rate

Fire intensity allocated in this research has been assessed with the heat release rate derived from Philadelphia's subway fire incident, and the value of 20MW has been applied to 60106 Btu/h (17.58MW) in consideration for safety factor. This is a value that conforms to the heat release rate of L.A. (21.4MW) and Boston (20MW) transit ways, which are lines recently established in accordance to NFPA regulations.

2.4 Evacuation Criteria

Due to the lack in design standards for smoke exhaust facility during subway fire in South Korea, NEPA 130 (1997) has been based upon to limit atmospheric temperature in evacuation areas to 60°C during fire breakout and visibility in a smoke filled environment was prescribed so that reflectors that do not naturally emit light like gates, wall, stairways, and etc. can be distinguished from a 20 ft. (6.096 m) distance. Having applied such conditions, this research has adopted the conditions of NFPA 130 as standards for evaluating ventilation facility's appropriateness.

2.4.1 Calculating Limit of Smoke Density

Visibility is evaluated in accordance to extinction coefficient. The relationship between light intensity of the light source (Io) and light intensity of the light recipient source (I), and extinction coefficient (K) are as shown in equation (1):

$$I/Io = e^{-KL} \tag{1}$$

Extinction coefficient is influenced by smoke particle density, and the relationship between extinction coefficient (K) and density of smoke particle is as shown in equation (2):

$$K = Km \cdot \rho Ys \tag{2}$$

Here, .: Specific extinction coefficient has a value of 7.6 m^2/kg and the relationship between extinction coefficient (K) and visibility distance (S) is as shown equation (3):

$$S = C/K \tag{3}$$

$$\rho Ys = C/(Km \cdot S) \tag{4}$$

Where,

I_o: light intensity of the light source[W/m^2]
I: intensity of the light recipient source[W/m^2]
K: extinction coefficient [m^{-1}]
ρYs: density of smoke particulate [mg/m^3]
Km: Specific extinction coefficient [m^2/kg]
S : visibility distance [m]
T : temperature [°C]

Here, C applies differently as a constant that depends on soot types and conditions; however, C=3 is applies to general reflectors. Consequently, NFPA's standard, one that states reflectors like gates or walls must be distinguishable from a 20 ft. (6.096 m) distance, was calculated as equation (4) to allocate limit of smoke density at 65 mg/m^3.

3. Fire Simulation Method

3.1 Temperature and Smoke Density Analysis

In order to study the smoke and intense heat elimination effects, FDS (Fire Dynamic Simulator) Version 3, currently in development by NIST (National Institute of Standards and Technology), has been used. The LES (Large Eddy Simulation) model and a mixture fraction model for turbulence flow field analysis and as the fire spread model, respectively. Furthermore, the control volume method was used as a means to analyze radiation heat transfer. Fire breakout refers to its occurrence in a stopped subway train and is a condition where one train car from middle of the train is destroyed by fire. The ignition point was selected as being the point 2.6 m above the rails. Having set the condition of a blazing subway train reaching the platform to rapidly diffuse fire as the analysis, calculations were made based on 300 seconds of evacuation time.

Fig. 5 indicates the grid generation and zone division applied to the analysis and total grid was 64,800 (90 × 360 × 20).

3.2 Calculation Parameters

Smoke exhaust in tunnels was not performed in cases 1,5 and 6, and cases 2, 3, and 4 indicated changes in in/out-flow volume and direction depending on smoke

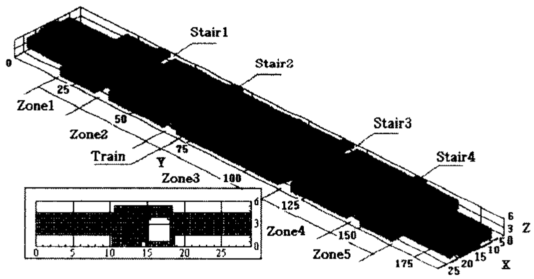

Fig. 5. Grid generation and zone division.

Table 4. Mechanical ventilation amount of fan shaft & track exhaust system

Case	Mechanical Ventilation Amount (m^3/min)							
	Fan shaft at left tunnel			Track Exhaust System at Platform		Fan Shaft at right tunnel		
	L1	L2	L3	UP	DOWN	R1	R2	R3
1	-	-	-	-	-	-	-	-
2	↑3647	↓7669	↑3672	↑40%	↑60%	↑3694	↓7397	↑3731
3	↑3604	↑7601	↑3611	↑40%	↑60%	↑3665	↑7354	↑3666
4	↓3610	↓7635	↓3612	↑40%	↑60%	↑3649	↑7376	↑3670
5	-	-	-	↑ 100%	-	-	-	-
6	-	-	-	-	↑ 100%	-	-	-
	*Up and Down separate percentage for the total TES exhaust amount, 3700 m^3/min Operating Mode: ↑ : Exhaust ↓ : Intake l : stop							

exhaust methods. Hence, pressure boundary conditions were applied in cases 1, 5, and 6 and calculations were made having applied SES simulation results as boundary conditions in cases 2, 3, and 4. for FDS. Table 4 shows smoke exhaust modes, and displays air inflow and outflow rates per smoke exhaust mode based on SES analysis results.

4. Results

4.1 Heat and Smoke Exhaust Effects

With the purpose of deriving the most optimal smoke ventilation mode in safely evacuating passengers during fire, the six types of smoke exhaust operation modes from Table 4 were analyzed to compare their heat and smoke exhaust effects. With a fire blazing subway train stopped at the platform as its subject, Fig. 6 shows graphical expression of temperature distribution and Fig. 7 shows smoke density distribution at 300 seconds from starting of fire event.

Fig. 6 shows platform temperature distributions which are compared by each case. Case 1 has shown a relatively high temperature distribution of $80^{\circ}C<T<100^{\circ}C$. Generally, it was found that heat dispersion effects on platforms in cases 2, 3 and 4, where tunnel fan shaft ventilation in main the tunnel area and TES were simultaneously converted to smoke exhaust mode, were superior to those found in cases 5 and 6 that are formed with TES only. Case 3 shows temperature distribution of $T<60^{\circ}C$ were over the entire platform area. Case 4

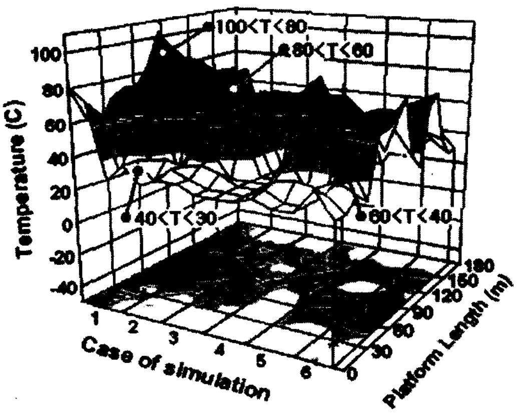

Fig. 6. 3D Temperature distributions & contour of platform for 6 case.

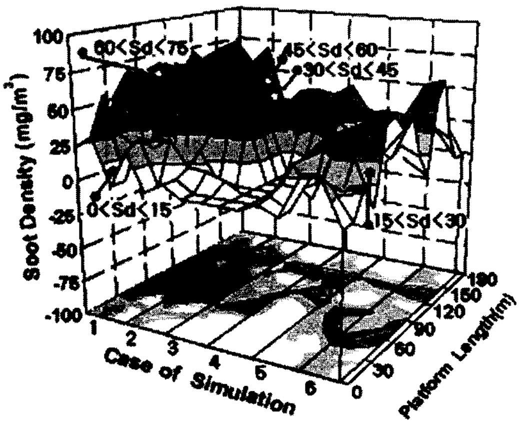

Fig. 7. 3D soot density distributions & contour of platform for 6 case.

shows low temperature distribution of $30^{\circ}C<T<40^{\circ}C$ were sustained in areas where fresh air inflows due to push-pull's characteristic but showed a rapid increase of $60^{\circ}C<T<80^{\circ}C$ when passing over fire location. In case 5, smoke exhaust mode is only operated on the upper section of the TES without tunnel fan shaft ventilation. In case 6, smoke exhaust mode is formed only on the lower section of the TES without tunnel fan shaft ventilation. Case 5 has formed a lower degree of temperature distribution than case 6 with the exception of fire area. Case 5 shows a temperature distribution $T<60^{\circ}C$ to show a considerable heat exhaust effect just by using upper TES.

Fig. 7 shows smoke density distributions by each case. Areas that surpass 65 mg/m^3, the highest concentration distribution, were found in cases 1 and 2. In case 3, for the most part, smoke density showed satisfactory values of $Sd<60$ mg/m^3. In case 4, exhaust only the upper side of TES proved to have relatively higher exhaust effect than simultaneously converting tunnel fan shaft ventilation to smoke exhaust mode. Furthermore, converting upper TES to smoke exhaust mode showed greater exhaust effects than through the lower TES alone.

4.2 Comparison of Average Platform Smoke Density and Temperature Field

Since basing on platform temperature and density distribution provides difficulties in absolute evaluation, platform temperature and smoke density averages were

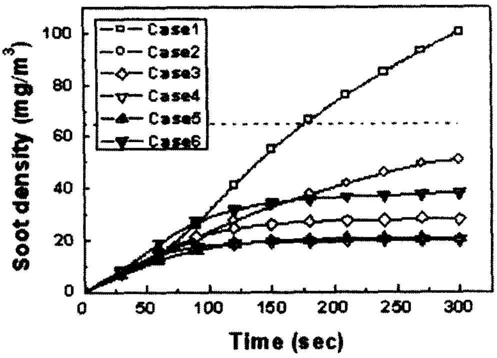

Fig. 8. Mean soot density above 1.5 m plan of subway platform.

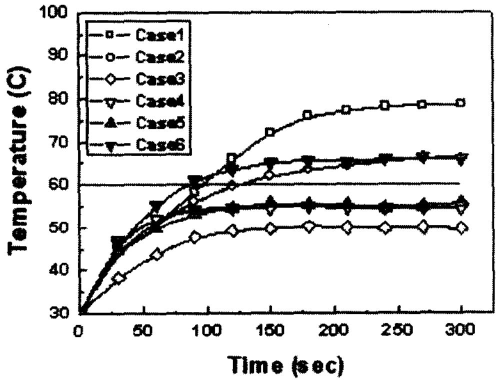

Fig. 9. Mean temperature above 1.5 m plan of subway platform.

calculated to compare 6 kinds of different ventilation scenarios.

Average temperature and average smoke density measured 1.5 m above the platform are displayed in Fig. 8 and Fig. 9. during 300 seconds from the starting of fire event.

Case 1 has shown an average density value of 65 mg/m^3 from 270-second elapses since the fire break out. Cases 2 to 6 succeeded in satisfying within 65 mg/m^3. The most effective smoke exhaust method were proven to be cases 4 and 5, and it was found that rather than utilizing tunnel fan shaft ventilation by converting to smoke exhaust mode, it was more effective to concentrate using TES around the fire source. Therefore, increasing the exhaust effectiveness of upper platform TES has been evidenced to be more effective. After 100-second elapses, cases 1, 2, and 6 showed unacceptable average temperature of 60°C, but cases 3, 4, and 5 showed satisfactory values.

The most effective heat exhaust method was found to be cases 3 and 4. Between theses two, it was concluded that case 3 has a superior quality in heat exhaustion even from initial stages of fire breakout. Consequently, converting all tunnel fan shaft ventilation to smoke exhaust mode has concluded to be most effective.

5. Conclusion

Conclusions derived from analyzing heat and smoke exhaust characteristics by each mode are as follows:

1. Large differences were found in platform heat environment and smoke density by types of smoke exhaust modes.

2. Basing on smoke concentration field, the most effective smoke exhaust mode in evacuation is using upper TES exhaust mode.

3. Push-pull mode showed smoke dispersion in lower parts of the fire obstructed passenger evacuation in areas located in the same direction of airflow from the very beginning of the simulation.

4. The most effective smoke exhaust mode was found to be case 3, where effective smoke ventilation characteristics were evident from initial stages of the simulation. Thus, converting all tunnel fan shaft ventilation to exhaust mode is most effective to remove heat.

5. As for smoke exhaustion, it was found that discharging at point of diffusion during break out of fire is more effective than diluting smoke density with outside air. As for heat exhaustion on the other hand, it is effective to accompany fresh air with thermal diffusion to discharge.

6. Under this research's parameters upper TES heat and smoke exhaust mode is the most effective focusing on visibility.

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