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Comparison of Two Different Smoke Extraction Schemes of Transversely Ventilated Tunnel Fire

Dong-Ho Rie, Hyung-Taek Kim[1], Ji-Oh Yoo[2], Hyun-Jun Shin[3] and Sung-Wook Yoon*[4]

Department of Safety Engineering, University of Incheon, Incheon 402-749, Korea
[1]Department of Advanced Materials Engineering, University of Incheon, Incheon 402-749, Korea
[2]Department of Building Mechanical Engineering,, Shinheong College Eujeongbu 480-701, Korea
[3]Department of Fire & Engineering Services Research, Korea Institute of Construction Technology, Goyang-Si 411-712, Korea
[4]GS Engineering & Construction, Research & Development Team, Seoul 135-985, Korea

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Abstract: In case of tunnel fire, one of the most effective facilities to save lives is the smoke control system. In this study, two different smoke extraction schemes of transversely ventilated tunnel were compared. One is the smoke extraction using the fixed exhaust ports on the false ceiling to achieve the uniform and distributed smoke extraction (uniform exhaust). The other is that using the remote controlled smoke extraction where only vents close to the fire is opened whereas the others are closed to enhance the limitation of the smoke spread (localized exhaust). A number of numerical simulations were performed to find out the optimal smoke extraction rate at each smoke extraction scheme to allow the tunnel users to escape to the safe area without endangering their lives by smoke.

Key words: tunnel fire; smoke; transverse ventilation; uniform exhaust; localized exhaust

1. Introduction

In the event of a underground or tunnel fire, one of the most effective facilities to save lives is smoke control system. We see evidences of this from fire accidents at the Mont Blanc tunnel, Channel tunnel, Hongjimoon tunnel and The subway station fire in Daegu, Korea. When a fire occurs in an underground space such as tunnel or subway, it's hard to expect that passengers make proper decision for the swift escape. In some cases, passengers believe that staying inside the car is safer than to evacuate, hence, lose a chance to survive. They wait inside the car for sometime but soon realize the severity of the situation and try to get away. The fires at the Daegu subway station and Mont Blanc tunnels prove this by the fact that most of the passengers died in the vicinity of the vehicles. For this reason, rapid notification of the emergency situation and guidance to the shelters are crucial, but the smoke control system plays the most important role in the fire emergency situation. In this study, some standards on the smoke exhaust rate at the bidirectional transversely ventilated tunnel is compared and numerical studies are carried out to find the efficiency of the two different smoke exhaust schemes, uniform and localized exhaust in terms of the limitation of the smoke spread.

2. Smoke Exhaust Schemes

When fire occurs in the road tunnel, smoke is either controlled or extracted using ventilation equipments. In smoke control system, smoke is controlled to keep smoke away from the shelters ensuring safety of the passengers for some time. In smoke extraction system, smoke is removed out of the tunnel using the smoke exhaust system. Longitudinal ventilation system adopts smoke control philosophy whereas transverse or semi - transverse ventilation system apply smoke extraction system. Hence, the longitudinal ventilation system has advantage in the local area and transverse or semi - transverse ventilation system is preferred in the tunnels

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*Corresponding author: yoonsw@gscoast.co.kr

located in the busy areas such as cities.

In this research, bidirectional semi-transversely ventilated tunnel is the target model for the study. There are two smoke extraction schemes applicable to the bidirectional semi-transversely ventilated tunnel using existing vents. One is the smoke extraction using the fixed exhaust ports(opening) on the false ceiling to achieve the uniform and distributed smoke extraction. This is defined as 'uniform exhaust'. The other is that using the remote controlled smoke extraction where only and large vents in the vicinity of the fire is opened whereas the others are closed. As only local vents are opened, this is defined as 'localized exhaust'.

Fig. 1 is the sketch of the uniform smoke exhaust system. In this system, openings are distributed every 5-20 m. In Fig. 2 the sketch of the localized smoke exhaust system is shown. Large and remote controlled openings are located every 50-200m to dedicate smoke exhaust capacity near The fire sport.

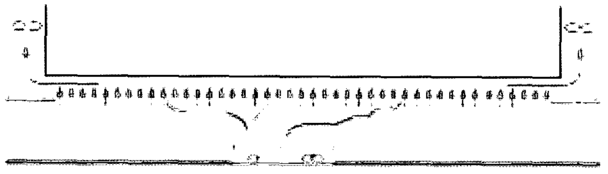

Fig. 1. Uniform exhaust system

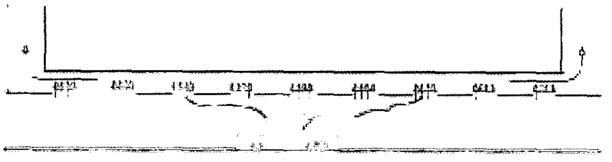

Fig. 2. Localized exhaust system

3. Comparison of Standards

The standard on the capacity of smoke exhaust system in a transversely ventilated tunnel has been provided by the NFPA 502 based on the experimental results of the Memorial tunnel, RABT of Germany, and CETU 02 of France. Vauquelin[5,6] and Kim[7] also reported their experimental results. According to those studies, required smoke exhaust quantity depends on the tunnel length, length of the smoke controlled area, fire strength and the air speed in the tunnel. However, elaborated methodology is yet to be expected. Table 1 shows some standards and experimental results. In standards of Germany and France, the additional amount of smoke extraction is required other than generated smoke itself. In Austria and Switzerland, 80 m^3/s is recommended for unit length of the tunnel, which corresponds to the smoke generation from the 30MW fire.

Table 1. Comparison of some standards on calculation of smoke exhaust capacity at the transversely ventilation tunne

Country	Exhaust capacity	comments
USA	Uniform ventilation 0.155 m^3·slane·m	186 m^3/s for each 600 m
Germany (RABT02)	$Q_E=A_r \cdot V_r+Q_s$	V_r=3.0 m/s 215.6 m^3/s for each 600 m
France (CETU 02)	$Q_E=A_r \cdot V_r+Q_s$	V_r=1.5 m/s Mont Blance tunnel : 80+45.2×1.5=147.80 m^3/s
Austria	≧ 80 m^3/s·fire zone	80 m^3/s
Switzerland	≧ 80 m^3/s·km	80 m^3/s
Kim et al.	0.17 m^3/s·m	102 m^3/s for each 600 m

The additional amount of smoke extraction recommended in the German and French standards, is considering air flow required to drive the smoke to the favored direction. It is expressed as the tunnel cross sectional area (A_r) multiplied by the longitudinal air velocity (V_r). Germany and France accounts for V_r as 3.0 and 1.5 m/s, respectively.

As seen in Table 1, the required smoke exhaust capacity differs for each country. However, in the most recent studies, the additional smoke extraction capacity is recommended for the control of the smoke movement as in the German and French standards.

The concept of longitudinal airflow for the control of the smoke movement was also applied in the enhancement of the ventilation system in the Mont Blanc and the Gotthard tunnel and they adopted jet-fans to control the smoke movement. The Nihonsaka tunnel adopted the saccardo nozzle for the same reason.

4. Simulation Methodology

4.1 Numerical Model

For the present study, FDS[11] (Fire Dynamics Simulation) is utilized and the dimension of the tunnel for the simulation is shown in Table 2.

For the uniform exhaust system, each opening has area of 1 m^2 and it is evenly distributed every 10 m for 800 m long (total 90 location) starting from 100 m behind the tunnel entrance to 100 m ahead of the exit. For the localized exhaust system. each opening has area of 12.2 m^2 and it is distributed every 100 m in the tun-

Table 2. Dimension of the Tunnel

Length (m)	Cross sectional Area(m^2)	Height (m)	opening interval	
			uniform	localized
1,000	60.8 (Duct Area: 10.6)	5.0	10 m opening area: 1 m^2 (90 locations)	100 m opening area: 12.2 m^2 (10 locations)

nel. The total of 12500000 (50(width) × 25(height) × 1000(length)) grids are generated for the numerical modeling. The fire strength applied is 20 MW and it is assumed that heat is generated at the surface of the car which has the surface area of 2.12 × 10 m. Fire is assumed to develop linearly from initiation and reaches its maximum strength in 4 minutes. The model is time dependent and the duration of the simulation is 600 seconds.

Exhaust capacity (Q_E) is defined in Equation (1) and smoke generation (Q_S) is fixed as 80 m^3/s. The longitudinal smoke control velocity (V_r) is varied as 0, 0.5, 1.0, 1.5, 2.0, 2.5 m/s to find optimal condition.

$$Q_E = A_r \cdot V_r + Q_s \tag{1}$$

where, Ar is tunnel cross sectional area. The velocity inlet boundary condition is applied for the simulation of smoke exhaust at openings.

4.2 Results

4.2.1 Uniform exhaust

Fig. 3 and Fig. 4 shows the profiles of soot density in case that no ventilation is operated and longitudinal smoke control velocity is differed as 0 and 2.5 m/sec, respectively. In the present study, it was assumed that the minimum soot density that affects the visibility are 65 mg/m^3 for reflecting object and 115 mg/ m^3 for not reflecting one.

Fig. 3 is the case that the longitudinal smoke control velocity is 0 m/s and it can be seen that the smoke is spreading evenly from the fire location to both ends of the tunnel. As seen in Fig. 5(a) and (c), smoke has spread 266.7 m to each ends from the fire source with the average speed of 1.1 m/sec in 6 minutes after the fire. The graph shows that the rate of increase in the smoke spread distance reduces with time.

Fig. 4 shows the longitudinal section view of the smoke spread in case that the longitudinal smoke control velocity is 2.5 m/s. As the smoke control velocity exists, smoke is spreading to the same direction as the smoke control air flow and reaches 250m from the fire source in 90 seconds after fire break out. Furthermore, the drop down rate of smoke layer is fast, hence, the possibility that the escapers are exposed to the untenable smoke condition is high. In road tunnels including bidirectional tunnels, there is a chance that the longitudinal air velocity is not balanced due to the natural wind effect or piston effect when the inflow of traffic is not balanced at both direction. If there is no ventilation, special consideration is required as the longitudinal spread and drop down rate of the smoke layer can be fast.

Fig. 5 shows the soot density and the smoke spread distance when uniform smoke exhaust is applied in the semi-transversely ventilated tunnel and no longitudinal smoke control is applied. Fig. 5(a) and Fig. 5(b) are the cases that Q_E are 80 m^3/s and 180 m^3/s, respectively. It is observed that both the longitudinal spread rate and drop down rate of smoke layer are decreasing with the increase of the smoke exhaust rate as expected. In Fig. 5(c) total of seven graphs show the inverse relationship

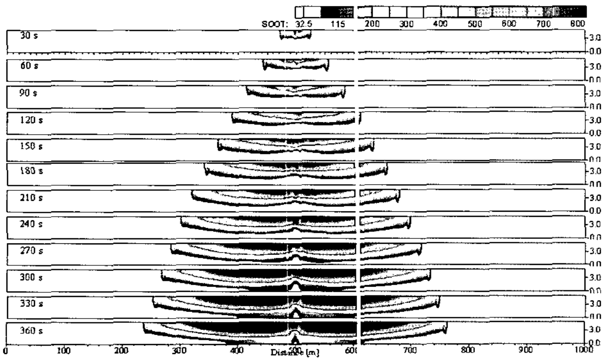

Fig. 3. Soot density (no ventilation, air velocity 0 m/s)

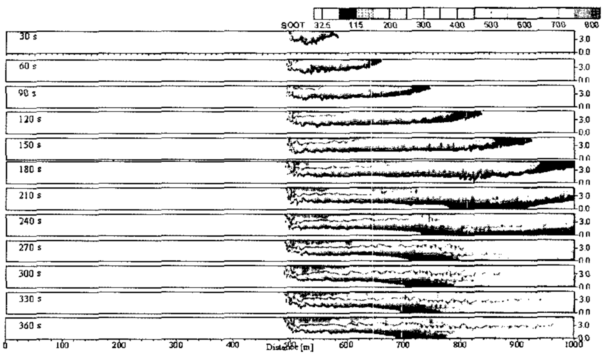

Fig. 4. Soot density (no ventilation, air velocity 2.5 m/s)

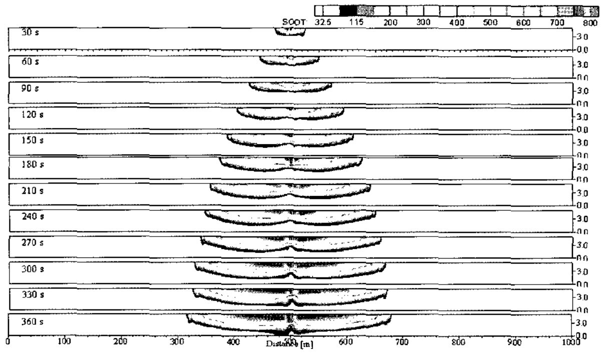

Fig. 5(a). Smoke spread in case that internal air velocity is 0 m/sec (uniform exhaust, exhaust rate: Q_E =80 + 0.0 Ar)

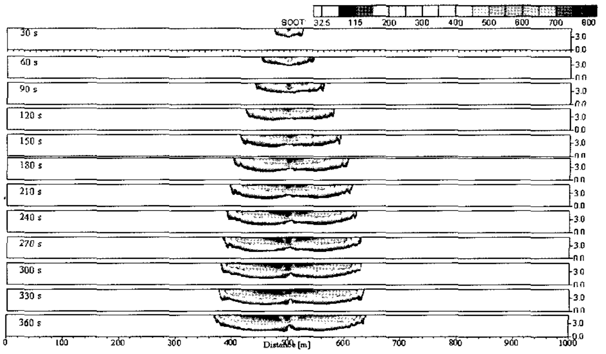

Fig. 5(b). Smoke spread in case that internal air velocity is 0 m/sec (uniform exhaust, exhaust rate: Q_E =80 + 2.0 Ar)

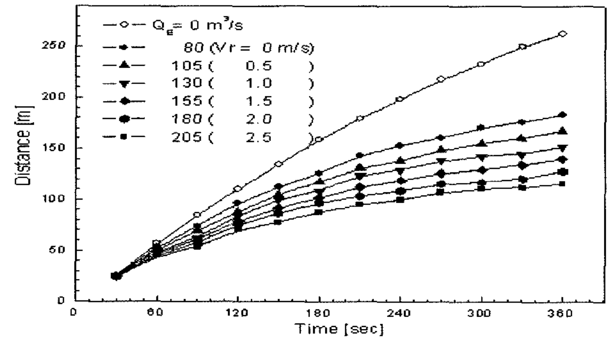

Fig. 5(c). Smoke spread distances when no internal air velocity exists. (uniform exhaust)

between the smoke exhaust quantity and the smoke spread distance.

In case of 80 m^3/s, the smoke exhaust rate, smoke spread distance is 183m in 5 minutes after the fire and this is 72% of smoke spread distance when no smoke exhaust is applied. In case of 205 m^3/s(Vr=2.5 m/s), smoke spread distance is about the half of that when no smoke exhaust is applied.

Fig. 6(a),(b),(c) show the smoke spread distance and soot density in case that the 2.5 m/s of air velocity is already formed inside the tunnel due to some effects such as natural wind.

In Fig. 6(a), smoke exhaust rate is 206 m^3/s (Q_E = 80 + 2.5 Ar) and it is shown that smoke traveling distance is over 250m. Hence, if the safety facilities is designed according to the current Korean standards on the tunnel safety facilities (escape time: 6 min, cross passage: 250 m, escape speed: 1.1 m/sec), the escapers can be endangered.

Fig. 6 (b) is the case that the smoke exhaust rate is increased to 231(Q_E = 80 + 3.0 Ar) which is 2.9 times of smoke generation rate (80 m^3/s) and the smoke spread distance does not increase noticeably with time after 270 seconds and distance of 227 m is maintained.

From graphs in Fig. 6(c), it is observed that there is limit value in the increase of smoke spread distance for each smoke exhaust rate and they are 405 m(205 m^3/s), 205 m(230 m^3/s) and 140(256 m^3/s), respectively.

From the analysis of the results, it can be concluded as follow. When the uniform smoke exhaust system is

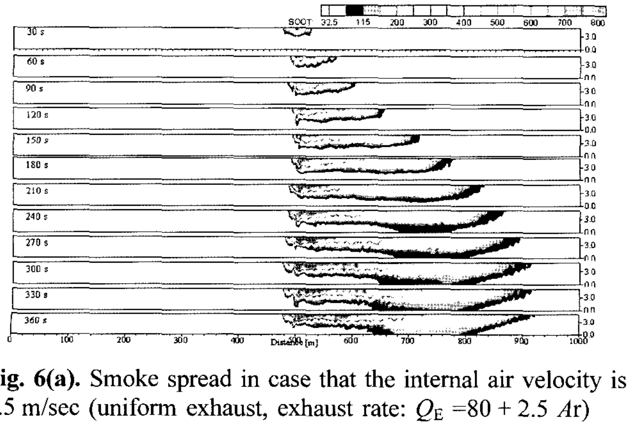

Fig. 6(a). Smoke spread in case that the internal air velocity is 2.5 m/sec (uniform exhaust, exhaust rate: Q_E =80 + 2.5 Ar)

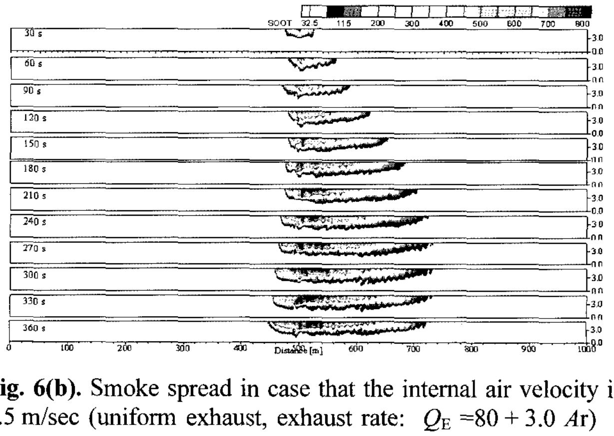

Fig. 6(b). Smoke spread in case that the internal air velocity is 2.5 m/sec (uniform exhaust, exhaust rate: Q_E =80 + 3.0 Ar)

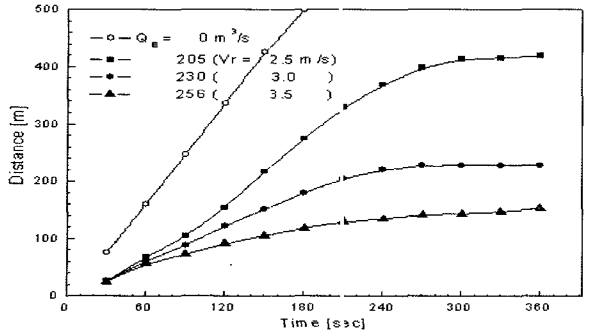

Fig. 6(c). Smoke spread distances when internal air velocity exists as 2.5 m/sec. (uniform exhaust)

applied in the bidirectional and semi-transversely ventilated tunnel, if the internal longitudinal air velocity is not formed, the smoke generation rate (80 m^3/s) suffices for the smoke exhaust rate to create the safe environment for the evacuation of tunnel users. However, in most cases, there exist longitudinal air velocity due to effects such as natural wind or piston effect by running cars, additional smoke exhaust capacity to control the smoke spread rate is need to be considered when designing the smoke exhaust system.

4.2.2 Localized exhaust

Fig. 7 is the case that the localized exhaust is applied to the bidirectional semi-ventilated tunnel and no longitudinal air velocity is already formed inside the tunnel.

In Fig. 7(a), the case is that the additional exhaust capacity other than the smoke generation is not considered (*Vr*=0 m/s, 80 m^3/s) and Fig. 7(b) shows the case when the smoke exhaust rate is 180 m^3/s. As expected, the smoke traveling distance decreases with the increase of the smoke exhaust rate.

Even in case that smoke exhaust rate is small as 80 $m^3/s(Q_E = 80 + 0.0$ Ar), smoke traveling distance is limited to 160 m to each ends of the tunnel. And when the exhaust rate is increased to 206 $m^3/s(Q_S = 80+2.5$ Ar) the smoke traveling distance reduces further as 100m.

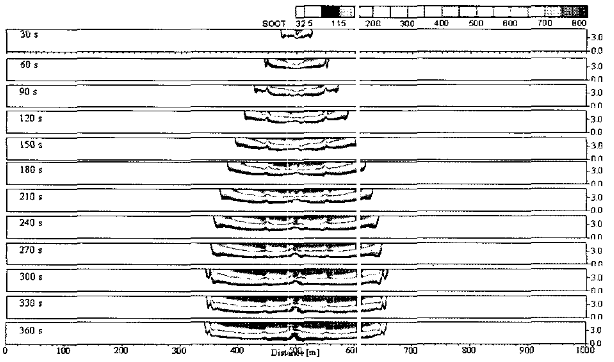

Fig. 7(a). smoke spread in case that the internal air velocity is 0 m/sec (localized exhaust, $Q_E = 80 - 0.0$ Ar)

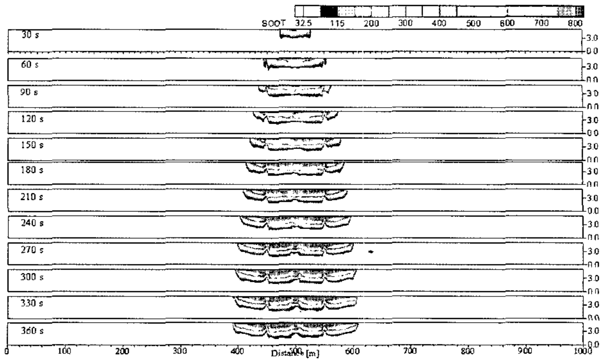

Fig. 7(b). smoke spread in case that the internal air velocity is 0 m/sec (localized exhaust, $Q_E = 80+2.0$ Ar)

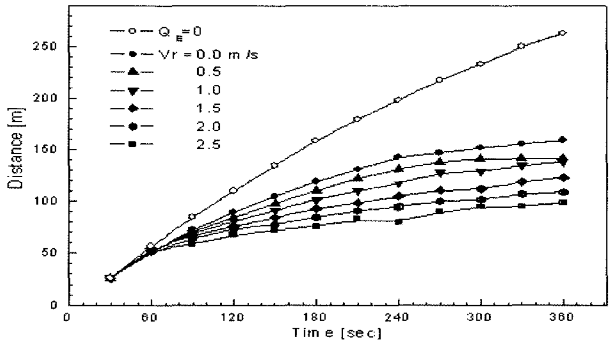

Fig. 7(c). smoke spread distances for each exhaust rate when no internal air velocity exists. (localized exhaust)

Fig. 8 is the case that the longitudinal air velocity of 2.5 m/s is already formed in the tunnel before the fire and smoke exhaust rate is 130 m^3/s ($Q_S = 80+1.0$ Ar) and 206 $m^3/s(Q_S = 80+2.5$ Ar) in the Fig. 8(a) and Fig. 8(b), respectively.

From the figures, it is observed that the smoke travels and passes the location of the very next opening in case of 130 m^3/s of smoke exhaust rate, In exhaust rate of 206 m^3/s, smoke spread distance is limited within the very next location of opening.

From the graphs in Fig. 8(c), in case of $Vr*Ar= 1.5Ar$ the smoke spread distance can be limited within the 250 m in 6 minutes after the fire breakout.

Hence, it can be concluded that in case of localized smoke exhaust in the bidirectional semi-ventilated tunnels, if the internal air velocity is maintained within the 2.5 m/s, Vr = 1.5 m/s suffices in the equation (1) to limit the smoke spread within the 250 m.

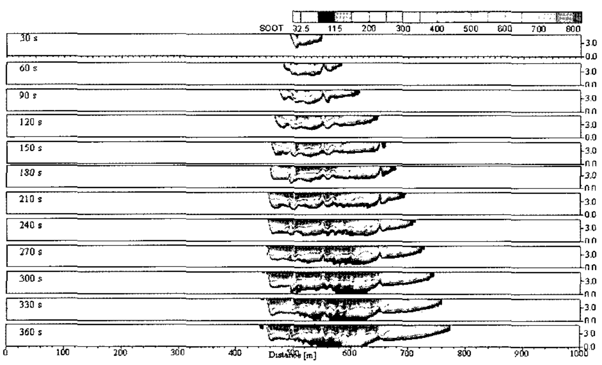

Fig. 8(a). smoke spread in case that the internal air velocity is 2.5 m/sec (localized exhaust, Q_E = 80 + 1.0 Ar)

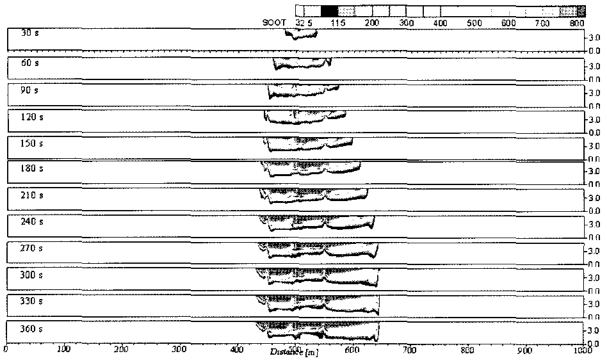

Fig. 8(b). smoke spread in case that the internal air velocity is 2.5 m/sec (localized exhaust, Q_E = 80 + 2.5 Ar)

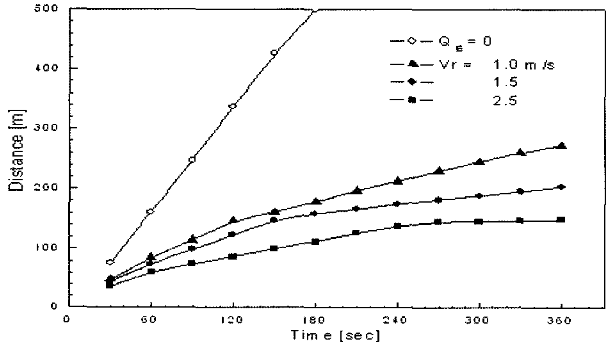

Fig. 8(c). smoke spread distances for each exhaust rate when internal air velocity exists as 2.5 m/sec (localized exhaust)

5. Conclusions

In this study, for decision of the optimal smoke exhaust capacity in case of fire in the semi-transversely ventilated road tunnel, several standards of nations were compared and numerical simulations were carried out in terms of smoke spread distance along with time. Following observations and conclusions can be made from the results.

1) The recent design trend of the smoke exhaust capacity in the semi-transversely ventilated tunnel is to increase the capacity over the smoke generation rate.

2) When there is no internal air velocity before the fire breakout, the smoke exhaust rate through the uniform openings as much as the smoke generation rate suffices to limit the smoke spread within 250m in 6 minutes after the fire.

3) However, if there exist the internal air velocity of 2.5 m/s or less, smoke exhaust rate of 231 $m^3/s(Q_E = 80{+}3.0Ar)$ with the uniform exhaust system is sufficient enough to limit the smoke spread within 250m in 6 minutes after fire. With the localized smoke exhaust system, exhaust rate of 155 $m^3/s(Q_E = 80{+}1.5Ar)$ can limit the smoke spread within 200 m in 6 minutes after fire.

4) Therefore, it is be concluded that for the safe evacuation of people in case of fire at the bidirectional semi-transversely ventilated tunnel, smoke exhaust capacity should be increased over the smoke generation rate and the localized exhaust system is more efficient than uniform exhaust system in limiting the smoke spread.

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