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Criteria for Fire Safety Design in Transversely Ventilated Tunnels Through a Model Tunnel Fire Experiment

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Abstract

To determine the key features of the fire safety design in transversely ventilated tunnels, smoke propagation characteristics are evaluated as a function of fire size, fire location and flow rates of supply and exhaust. A model of the Memorial tunnel is used. The scale-down ratio of its cross-section is 1/20 and its length is 12m. Fire sizes and ventilation rates in real tunnels are calculated by Froude similarity. In general, it is found that the smoke propagating distance is proportional to the fire size and is inversely proportional to the exhaust ventilation rate. When the location of the fire is off-centered, the smoke propagating distance increases remarkably as compared with a centered-fire scenario. A hazardous situation generated from an imbalance between the supply rate and the exhaust rate is also observed. Based on the results, smoke propagating distance and the ratio of supply to exhaust are suggested as criteria for fire safety design of a transverse ventilation system.

1. Introduction

In tunnel fires, if the fire smoke is not ventilated properly, tunnel users such as motorists may be trapped in the tunnel and thus placed in a life-threatening situation. Tunnel ventilation systems are categorized into two groups according to the main direction of the ventilating flow, longitudinal ventilation systems where the ventilation air flows along the tunnel and transverse ventilation systems where the ventilation air flows across the tunnel. Smoke behavior with ventilation systems is one of the decisive criteria for fire safety design in tunnels.

In the case of longitudinal ventilation, the critical velocity that prevents fire smoke from propagating upstream of the ventilation air is the main design parameter. The critical velocity can be estimated using many verified equations [1,2,3] and has been adopted in the design phase. At a velocity greater than the critical velocity, all smoke

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only propagates downstream of the fire. However, the entire cross-section of the downstream part of the tunnel is filled with the smoke. This situation is an inherent weak point of the longitudinal ventilation system and is the main reason why a transverse ventilation system should be used for long tunnels with heavy traffic load.

In the case of a transverse ventilation system, the main concern is determining an effective method to extract the smoke by a fresh air supply and exhaust, since the transverse ventilation system cannot confine smoke to moving in one direction. The recommended minimum installed capacity of 100CFM per foot (0.155m^3/sec per meter) of lane by ASHRAE[4] and of 0.08m^3/sec per meter of lane by PIARC[5] now serve as the minimum emergency criteria for tunnel fires. However, they are merely minimum criteria and do not consider smoke behavior such as propagating distance and smoke descent according to ventilation capacity and fire scenarios. Criteria for effective operation during a fire have thus far not been defined.

Smoke produced from a fire travels upward due to its buoyancy and changes its propagation direction to spread along a tunnel after impingement to the ceiling surface. There is a distance L at which the smoke propagation stops, because the smoke is extracted via the ceiling space, as seen in Fig. 1.

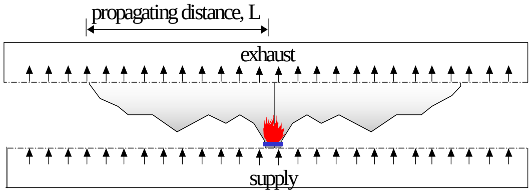


Figure 1. Definition of the smoke propagating distance in a transverse ventilation system

Therefore the smoke propagating distance L is an important design parameter for transverse ventilation because the smoke under the ceiling can descend to the tunnel floor due to possible turbulence generated from an imbalance between the supply and the exhaust, as described in FHWARD [6], and this poses a potential hazard in terms of life safety.

Vauquelin and Megret [7] investigated the smoke extraction capability in a tunnel with two exhaust ducts through model experiments. They evaluated the efficiency of the exhaust ducts with fire size, duct location, and duct shape. However, their work did not consider a real situation in transverse ventilation because their model employed only two extraction points at both sides of the fire.

The Memorial tunnel fire experiment[8] was carried out to evaluate the smoke control capabilities in a transverse ventilation system. Although the experiment provided some important information for real fires in transverse ventilation systems, there was no continuous control of experimental parameters because it was a real tunnel experiment. In this paper, through model tunnel fire experiments, smoke propagation characteristics in transverse ventilating systems are evaluated as a function of fire size, fire location, and flow rates of supply and exhaust in order to supplement full-scale tunnel tests. Based upon the results, several design parameters controlling the flow rates of supply and exhaust in transversely ventilated tunnels are presented.

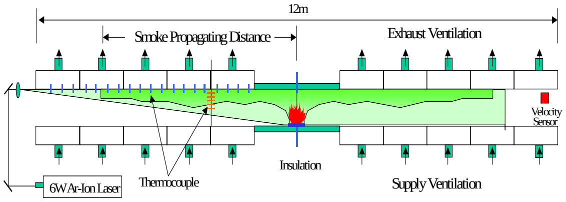
It was found that the smoke propagating distance in the experiment is proportional to the fire size and is inversely proportional to the exhaust ventilation rate. However, it was also discovered that the smoke propagating distance is strongly dependent on the fire location and the supply ventilation rate. In particular, when the supply rate is greater than the exhaust rate, a strong negative effect is observed in terms of life safety. For these reasons, the propagating distance should be included as a design parameter for transversely ventilated tunnels.

2. EXPERIMENTAL SETUP

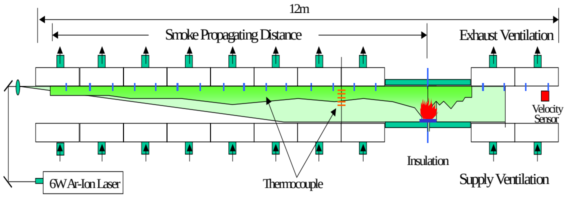
The model of the Memorial tunnel was used in this experiment. The Memorial tunnel is 8.8m in width, 4.4m in height excluding the ceiling duct, and its total length is approximately 810m. Figure 2 shows the experimental setup. The model's scale-down ratio of the cross-section is 1/20. The total length of the model tunnel is 12m. Fresh air was supplied through both sides of the tunnel floor and fire smoke was exhausted through equally spaced (25cm) slits with a breadth of 0.76cm on the ceiling. Uniform supply and exhaust along the tunnel were accomplished by 20 ducts, whose passages were controlled independently of each other, as shown in Figure 2. The model was manufactured by acrylic material for the visualization of smoke propagation except thermal insulation parts in the vicinity of the fire source.

Hepthane pool fires were used as fire sources. The fire size was calculated from the fuel mass reduction measured by a balance. The propagation and descent of the fire smoke were visualized by a laser sheet. A plane laser sheet was made by a 6W Ar-Ion laser and cylindrical lens. The laser sheet illuminates the smoke particles, thus smoke front and descent and mixing of smoke can be visualized, as shown in Figure 2(a), (b). To supplement results of smoke propagation and descent, temperature of smoke layer was measured by K-type thermocouples of diameter 0.1mm. The thermocouple’s temperature records can unambiguously detect the presence of the hot smoke, thus it supplements the visualization results.

To examine the effect of the fire location on smoke propagation, two different situations were considered. One is a symmetric case where the fire is located at the center of the tunnel, and the other is an asymmetric case where the fire is located at the right side of the tunnel.



(a) Symmetric case



(b) Asymmetric case

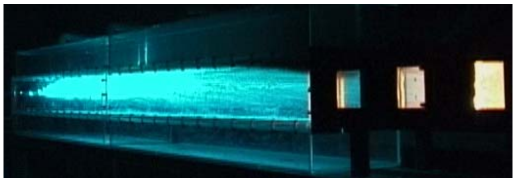
(c) Overview of model tunnel

(d) Flow control and measurement site

Figure 2. Experimental setup

3. RESULTS AND DISCUSSION

Smoke propagation is one of the key features for fire safety design in tunnels. The flow rates of fresh air supply and exhaust, through the floor and the ceiling respectively, determine the smoke propagating distance in transversely ventilated tunnels. The smoke propagation characteristics in a transversely ventilated tunnel are evaluated as a function of the fire size, the fire location, and the flow rates of supply and exhaust through model tunnel fire experiments.



(a) Smoke propagation

(b) Fire (c) Smoke front

Figure 3. Photographs of the model tunnel experiments

The smoke propagation, the fire, and the smoke front are shown in Figure 3 in a transversely ventilated model tunnel. In Figure 3-(c), it is clearly shown that the smoke front stops at a certain point.

3.1 Symmetric Case

When the fire is located at the center of the tunnel, the physical phenomena are symmetric to the tunnel center. The flow field inside the tunnel is determined as follows.

When the exhaust rate is greater than the supply rate, the fresh air introduced from outside results in a longitudinal velocity field toward the tunnel center. In this case, propagating against the ongoing longitudinal velocity field, the smoke originated from the fire is exhausted along the ceiling. On the contrary, when the exhaust rate is smaller than the supply rate, the smoke is exhausted along the ceiling, propagating together with the outgoing longitudinal flow field.

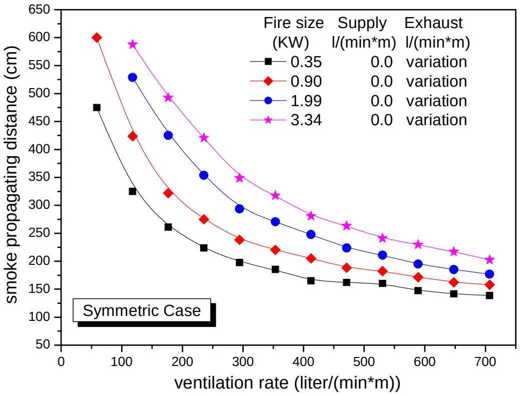


Figure 4. The smoke propagating distance according to the exhaust rate (symmetric case)

Figure 4 shows the effect of the exhaust ventilation on the smoke propagating distance. The horizontal axis represents the ventilation rate per unit tunnel length and the vertical axis represents the smoke propagating distance from the fire, respectively. In the case where the supply rate is zero, the smoke propagating distance increases with increasing fire size and decreases with increasing exhaust ventilation rate.

The effect of the supply ventilation on the smoke propagating distance is demonstrated in Figure 5. With a supply rate of 117.8 liter/min per meter, it is revealed that the propagating distance according to the exhaust ventilation shows no remarkable difference in comparison with the case of no supply rate. However, as the exhaust rate is decreased, it was observed that the smoke front descends toward the tunnel floor. In particular, when the exhaust rate is smaller than the supply rate, it was found that the smoke fully mixes with the ventilating air and abruptly spreads across and along the tunnel. In these circumstances, there is no propagating distance data in Figure 5, since the whole cross-section of the tunnel filled with the smoke.

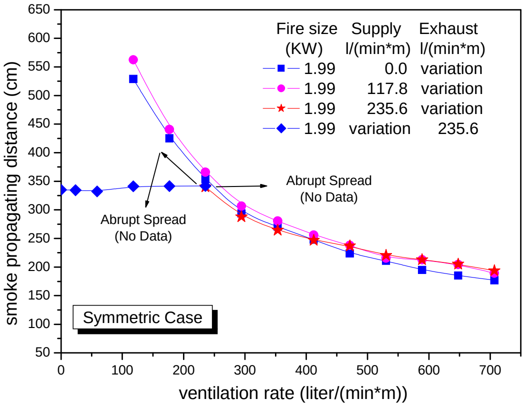
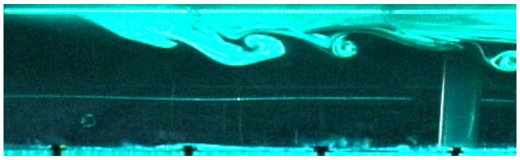


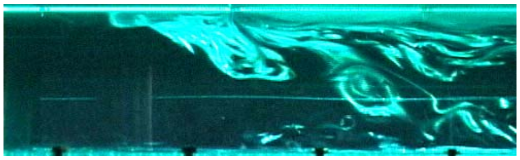
Figure 5. Effect of the supply rate on the smoke propagating distance (symmetric case)

This tendency of smoke propagating distance with supply ventilation is clearly shown as the supply rate is varied and the exhaust rate is constant at 235.6-liter/min·m, in Figure 5. When the supply ventilation rate is smaller than the exhaust ventilation rate of 235.6-liter/min·m, the smoke propagating distance is scarcely dependent on the supply rate. However, when the supply rate exceeds the exhaust rate, abrupt mixing and spread occur, and the smoke spreads within the whole region of the tunnel. This is a hazardous situation for life safety as described qualitatively in FHWARD [6].

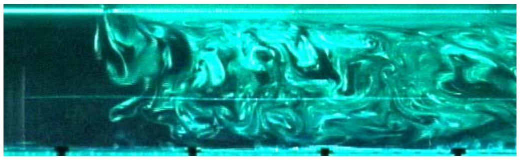
Figure 6 shows descent and mixing of the smoke in the vicinity of the smoke front. When exhaust ventilation only is provided (Figure 5-(a)), the smoke propagates along the ceiling, forming a thin layer. With a supply rate that is 25% of the exhaust rate, smoke descends to the tunnel floor, mixing with ventilating air. As the supply ventilation rate increases, the smoke further descends and mixes. However, supply ventilation rates that are less than the exhaust ventilation rates do not affect the smoke propagating distance. When the supply rate exceeds the exhaust rate, the whole region of the tunnel is filled with fully mixed smoke.



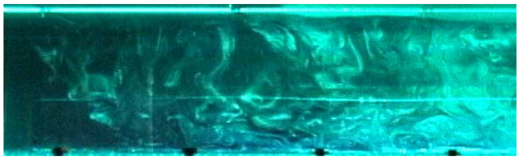
(a) supply ventilation rate = 0 liter/min·m



(b) supply ventilation rate = 58.9 liter/min·m



(c) supply ventilation rate= 117.8 liter/min·m



(d) supply ventilation rate= 235.6 liter/min·m

Figure 6. Effect of the supply rate on the smoke propagating distance (symmetric case, exhaust ventilation rate = 235.6 liter/min·m)

3.2 Asymmetric Case

When the fire occurs at an off-centered location (see Figure 2-(b)), the physical phenomena are asymmetric to the tunnel center and to the fire location. The flow field inside the tunnel is determined as follows.

If the exhaust rate is greater than the supply rate, the fresh air introduced from outside results in a longitudinal velocity field toward the tunnel center. In this case, the smoke generated from the fire behaves in a variety of manners according to the propagating directions. In the case where the smoke propagates to the right-hand direction, the smoke is exhausted along the ceiling, propagating against the ongoing longitudinal velocity field to the tunnel center. In the case where the smoke propagates to the left, the smoke is exhausted along the ceiling, propagating in company with the longitudinal velocity field directed to the tunnel center. On the contrary, if the exhaust rate is smaller than the supply rate, a longitudinal velocity field from the tunnel center to the tunnel portals is formed. Therefore the smoke travels in an opposite manner to the case where the exhaust rate is greater than the supply rate.

In the asymmetric case, since the fire is located at the right side of the tunnel, the smoke does not propagate to the right side due to the strong opposing longitudinal velocity field (strong exhaust ventilation), or a portion of the smoke goes outside the tunnel (weak exhaust ventilation). Since we have an interest in the motion of the smoke captured inside the tunnel, the smoke propagation to the left side is considered in this work. (see Figure 2-(b))

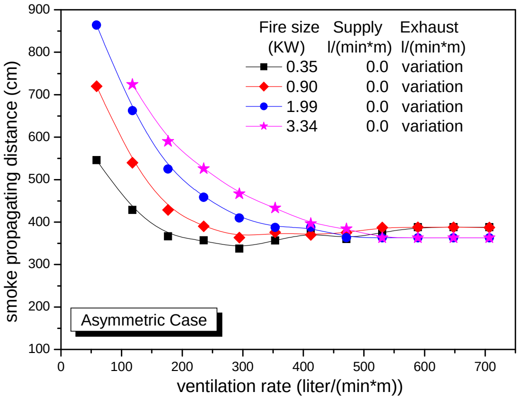


Figure 7. The smoke propagating distance according to the exhaust rate (asymmetric case)

Figure 7 shows the effect of the exhaust ventilation on the smoke propagating distance. The horizontal axis represents the ventilation rate per unit tunnel length and the vertical axis represents the smoke propagating distance from the fire. In the case where the supply rate is zero, the smoke propagating distance increases with increasing fire size and decreases with increasing exhaust ventilation rate, as in the symmetric case. However, even if the exhaust rate increases, the smoke propagating distance does not decrease continuously, but approaches to a constant value. This is due to the strong longitudinal velocity field directed to the tunnel center. That is, the smoke always propagates up to a certain location together with the strong longitudinal velocity field. This implies that there is a certain limit to which the smoke propagating distance can be reduced for the off-centered scenario in the transverse ventilation system. The limit position is in the vicinity of the tunnel center where the longitudinal velocity is stagnant.

Therefore, the off-centered fire scenario should be considered in the design of a transverse ventilation system and a measure to reduce the strong longitudinal velocity field should be devised.

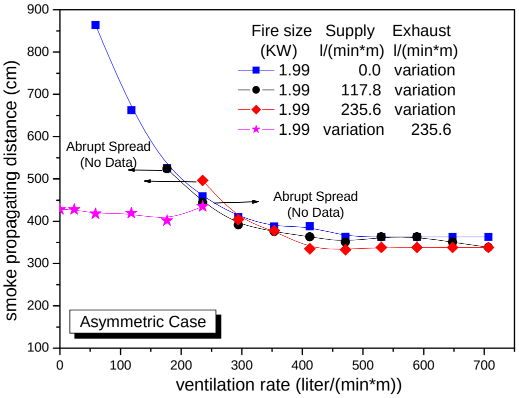


Figure 8. Effect of the supply rate on the smoke propagating distance (asymmetric case)

Figure 8 shows the effect of the supply ventilation on the smoke propagating distance in the asymmetric case. As in the symmetric case, it is also discovered that the propagating distance with the supply ventilation shows no remarkable difference in comparison with the case of no supply rate, but if the supply rate is greater than the exhaust rate, the smoke is abruptly mixed with the ventilating air and it spreads across and along the tunnel. This suggests that in a transverse ventilation system the supply rate that are more than the exhaust rate induces a hazardous situation for life safety, regardless of the fire scenarios (centered or off-centered).

3.3 The smoke propagating distance in real tunnels

The smoke propagating distance in real tunnels can be predicted from the measured distance in the model tunnel by Froude similarity as follows [9,10]:

$$\frac{\dot{Q}_M}{\dot{Q}_F} = \left(\frac{L_M}{L_F}\right)^{5/2}, \quad \frac{V_M}{V_F} = \left(\frac{L_M}{L_F}\right)^{1/2}$$

where $\dot{Q}$, V, and L denote fire size, velocity, and length, and subscripts M and F indicate mean model and full-scale tunnel. From the above equations, the smoke propagating distances in symmetric and asymmetric cases are shown in Figures 9 and 10, respectively.

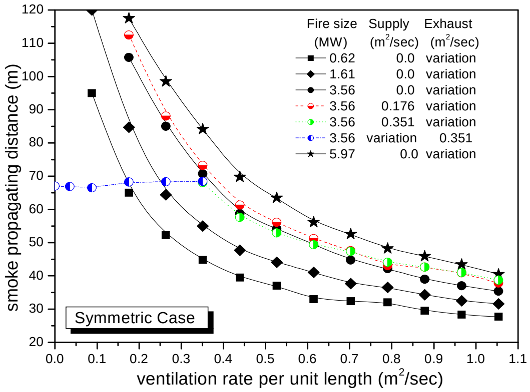


Figure 9. The smoke propagating distance in a real tunnel (symmetric case)

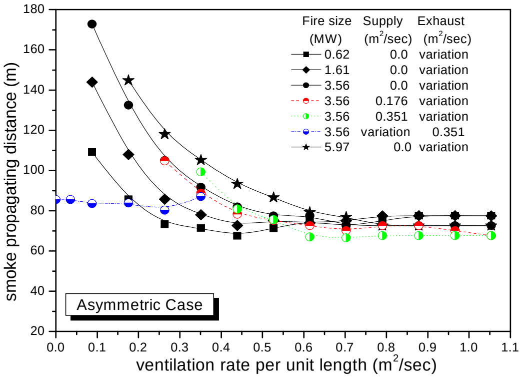


Figure 10. The smoke propagating distance in a real tunnel (asymmetric case)

In the case of 5.97MW, no supply, and an exhaust rate of 0.35m^2/sec, the distance is about 85m in the symmetric arrangement but about 105m in the asymmetric one. This discrepancy between the symmetric and asymmetric cases results from the different longitudinal velocity fields, as noted in Section 3.1 and 3.2. The importance of the longitudinal velocity field in transverse ventilation was investigated by Mizuno and Ichikawa [11]. They suggested that the suppression of longitudinal airflow is strongly desired in order for those trapped in the runnel to safely evacuate. However, in our results, the longitudinal velocity field has two kinds of effects on evacuation, a positive effect reducing the smoke propagation in a symmetric fire scenario and a negative effect inducing the smoke propagation in an asymmetric fire scenario.

The transverse ventilation rates of major road tunnels are illustrated and compared with the present results in Table 1. These rates comply with the recommendations of ASHRAE [4] (0.155m^3/sec per meter of lane) and PIARC [5] (0.08m^3/sec per meter of lane). The exhaust ventilation rate is known to be only 50-60% of the total ventilation rate in fully-transversely ventilated tunnels.

Tunnel	Length /Ventilation Type	Total Ventilation Rate	Ventilation rate per meter

Memorial Tunnel Experiment	0.81km/ Supply and Exhaust		0.078 ~ $0.31 m^2/s$
Typical Long Road Tunnels in Alps	9.25 ~ 13.5km/ Supply and Exhaust	2000 ~ $3540 m^3/s$	0.132 ~ $0.382 m^2/s$
Model Tunnel, KIMM	Supply and Exhaust		Figure 9 and 10

Table 1. Transverse ventilation rates of major road tunnels

Figure 10 and Table 1 indicate that the smoke propagating distance of typical long road tunnels will be about 90 ~ 170m with a 3.6MW off-centered fire, which represents a small passenger car fire only, even if the full ventilation capacity is used as the exhaust ventilation. The fire size is generally estimated from 20MW (public bus fire) to more than 100MW (petrol tanker fire) in tunnel fire safety design [12]. Therefore, it may be noted that the ventilation rates in Table 1 are not sufficient for fire safety design, because the smoke propagation inside tunnels poses potential danger for evacuation, and the supply is not only ineffective for smoke extraction, but also dangerous.

4. CONCLUSIONS

Smoke spread in a model tunnel with a transverse ventilation system was analyzed in terms of fire size, fire location, and variation of the supply rate and the exhaust rate. Based on the experiments, the important results can be summarized as follows:

1. The smoke propagating distance was proportional to the fire size and inversely proportional to the exhaust ventilation rate.

2. In the case of an off-centered fire, even if the exhaust rate increased, the smoke propagating distance did not decrease continuously, but approached a constant value. In general, the attainable minimum distance of smoke propagation for an off-centered fire was clearly greater than that for a centered-fire scenario.

3. The supply rate did not have a remarkable effect on the smoke propagating distance when it was smaller than the exhaust rate. If the supply rate was larger than the exhaust rate, the whole cross-section of the tunnel filled with smoke, a clearly negative phenomenon in terms of fire safety design.

4. When the results of the model tunnel experiments were extended to real-scale tunnels using Froude similarity, the smoke propagating distance of typical long road tunnels was estimated at more than 90m for the fire size of only 3.6MW even if the full ventilation capacity was used as the exhaust ventilation.

5. We suggest the smoke propagating distance and the ratio of supply to exhaust as criteria for fire safety design of a transverse ventilation system

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