EXPERIMENTAL INVESTIGATIONS ABOUT VISIBILITY IN A FIRE ACCIDENT USING A SCALE MODEL TUNNEL

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ABSTRACT
This study investigated the visibility of occupants in a tunnel fire experiment using a large-scale model tunnel. It is important to understand how well the occupants can see during a fire in a tunnel to simulate evacuation and assess the safety of a tunnel in case of fire. The value of visibility can only determine whether occupants in a fire can evacuate or not, due to loss of visibility caused by smoke and being unable to move before dying from smoke inhalation. The ventilation system in a tunnel may make it safer for occupants to evacuate in a fire. In Japan, the borderline for the extinction coefficient is 0.4 m⁻¹ before occupants cannot evacuate. However, this is based on building experiments, and building fires are different from tunnel fires. Therefore, we investigated the situation of occupants using a fire in a large-scale model tunnel, by asking the subjects to enter the experimental fire and then fill out a questionnaire. The model tunnel was 1 m high, 2 m wide and 41.4 m long, which is a scale ratio of 1/5. In this study, about half of the subjects thought that they could evacuate under the smoke layer, but almost all of them thought they could not evacuate when the extinction coefficient was 0.37 m⁻¹.

Keywords: scale model tunnel, tunnel fire, similarity law, visibility, smoke behavior, evacuation environment, risk analysis

1. INTRODUCTION
Fires are a serious disaster, and it is important to design refuges in places where there are many people in case of fire. When occupants are faced with a fire in a road tunnel, they must decide whether they can evacuate. This is divided into the psychological aspect of occupants’ feeling (psychological factors) and the occupants’ environmental aspect (physical factors). The physical factors that are currently used to design refuges are temperature, poisonous gas and smoke. The former two are used in disaster prevention in European tunnels. However, in a tunnel fire, there may be many people along the length of the tunnel, and one major factor in sensing danger in a tunnel fire is that the psychological situation of occupants changes when they see the smoke, which is a physical factor, and then decide to evacuate. Therefore, occupants determine whether to evacuate under psychological factors, which are influenced by physical factors, hence this relationship is very important [1], [2]. In this study, the subjects experienced a tunnel fire in a large-scale model tunnel, then filled in a questionnaire about whether they thought they could evacuate from the tunnel fire or not. The visibility in the tunnel corresponding with the results of the questionnaire was measured by using optical smoke density. The pictures of smoke movement were taken by a video camera. We examined the relationship between the optical smoke density in the tunnel and the possibility of evacuation of occupants in a tunnel fire.
2. LARGE-SCALE MODEL TUNNEL

Figure 1 shows a view of the large-scale model tunnel, which was 41.4 m long (x-coordinate), 2 m wide (y-coordinate), and 1 m high (z-coordinate). The model tunnel was rectangular in cross section, and was designed considering the laws of similarity. Table 1 lists the parameters of the tunnel, which was on a scale of about 1/5.

![Figure 1: Large-scale model tunnel](image)

Figure 2: Schematic diagram of the longitudinal section of the tunnel

In model experiments, it is important to produce turbulent flow in the model tunnel as well as a full-scale tunnel. The model tunnel in this study was large, with a Reynolds number $Re$ in the tunnel of 40,000 or more, and hence complete turbulent flow was achieved in the tunnel.

The heat transfer from thermal fumes to the tunnel walls is an important governing phenomenon in a tunnel fire. This heat transfer is governed by conduction heat transfer characteristics for the wall materials, and by convection heat transfer characteristics for the surface of the walls. Table 1 indicates the Biot number $Bi$ and the Fourier number $Fo$ concerning the thermal characteristics of tunnel walls. The Biot and Fourier numbers of the model tunnel in this study are close to those of an actual concrete tunnel. Autoclaved lightweight aerated concrete (ALC) panels were used as the wall material of the tunnel in this study.
Figure 2 shows a schematic diagram of the model tunnel. A stainless steel combustion vessel was installed as a fire source in the center, 40 m from the open end of the tunnel, with a fan located as shown. The position of the fire source is the origin of coordinates.

**Table 1:** Specifications of large-scale model tunnel and full-scale tunnel [3]

<table>
<thead>
<tr>
<th></th>
<th>Large-scale model tunnel</th>
<th>Full-scale tunnel (example)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shape</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height $H$ [m]</td>
<td>1.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Width $W$ [m]</td>
<td>2</td>
<td>10.0</td>
</tr>
<tr>
<td>Cross-sectional area [m$^2$]</td>
<td>2</td>
<td>50.0</td>
</tr>
<tr>
<td>Equivalent hydraulic diameter [m]</td>
<td>1.316</td>
<td>6.667</td>
</tr>
<tr>
<td><strong>Scale ratio</strong></td>
<td>$\gamma$</td>
<td>1/5</td>
</tr>
<tr>
<td>Froude number $Fr$</td>
<td>0.160</td>
<td>0.160</td>
</tr>
<tr>
<td>Reynolds number $Re$</td>
<td>$4.2 \times 10^4$</td>
<td>$4.7 \times 10^5$</td>
</tr>
<tr>
<td>Biot number $Bi$</td>
<td>41.2–117.6</td>
<td>21.9–62.5</td>
</tr>
<tr>
<td>Fourier number $Fo$</td>
<td>$6.41 \times 10^{-8}$</td>
<td>$2.37 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

n-heptane and toluene were used as liquid fuels for the fire source. The mass loss rate of the fuel was measured by an electronic balance. The heat release rate of the fire source was calculated from the mass loss rate. The temperature inside the model tunnel was measured by K-type thermocouples of 0.1 mm diameter with a small time constant, which were placed on the ceiling and central longitudinal section. Six smoke meters were installed at 0.1 m intervals from 0.4 m to 0.9 m above the tunnel floor at three locations: 18 m, 24 m, and 38 m from the fire source.

Concentration of smoke ($C_s$), which is a kind of optical smoke density generally used in studies on tunnel fires, was used to measure smoke density. $C_s$ density was averaged by the tunnel’s width. It was calculated as an extinction coefficient in the Lambert-Beer equation as follows:

$$C_s = -(1/l) \ln \left(\frac{I}{I_0}\right)$$

where, $I$: intensity of incident light, $I_0$: intensity of transmitted light (non-smoke), and $l$: distance traveled by light through the gas ($l = W = 2$ m).

In both the real tunnel and model tunnel, $(I/I_0)$ between two corresponding points must be identical for the same influence of smoke on visibility. Accordingly, $C_s$ density of a full-scale tunnel, $C_{sf}$, $C_s$ density of the model-scale tunnel, $C_{sm}$, and $\gamma$ as the scale ratio ($=1/5$) have the following relation:

$$C_{sm} = C_{sf} / \gamma$$

That is, $C_{sf} = 0.4$ m$^{-1}$ in full scale is $C_{sm} = 2$ m$^{-1}$ in model scale. Note that $C_s$ and the extinction coefficients in the following sections are identical to $C_{sf}$ which was converted from the experimentally obtained value of $C_{sm}$.
3. EXPERIMENTS

3.1. Experimental conditions

In this study, we considered only non-ventilation velocity, in which the exit near the fire source is closed. Table 2 shows the experimental conditions. Two kinds of fuel (case A and case B) were used as the fire source to vary the smoke generation rate. The average heat release rates of the two fire sources were almost the same, but the fuel in case A generated much more smoke, and the extinction coefficient became 0.37 m\(^{-1}\) as the smoke spread, but was only 0.1 m\(^{-1}\) in case B in the same situation. Converting the average heat release rate into full-scale using Froude’s law of similarity for a scale ratio \(\gamma = 1/5\), the fire scale, which was about the heat release rate for a minibus fire, was obtained.

Table 2: Experimental cases

<table>
<thead>
<tr>
<th>Experimental case</th>
<th>Fuel n-heptane : toluene</th>
<th>Burning area ([m^2])</th>
<th>Average heat release rate (quasi-stationary) ([MW])</th>
<th>Average heat release rate (converting to full-scale) ([MW])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>0 : 10</td>
<td>0.085</td>
<td>0.20</td>
<td>11</td>
</tr>
<tr>
<td>Case B</td>
<td>3 : 7</td>
<td>0.085</td>
<td>0.18</td>
<td>10</td>
</tr>
</tbody>
</table>

3.2. Questionnaire for subjects, and experimental contents

In this experiment, all the subjects wore a protective mask, entered the tunnel at the \(x = 21\) m point, observed the situation during the fire experiment, and then answered the questionnaire on whether they thought they could evacuate or not. Video cameras were installed in the same place to photograph the situation experienced by the subjects. In addition, questionnaires were distributed during the experiment, with four multiple-choice responses to avoid ambiguity: (i) possible, (ii) probably possible, (iii) probably impossible and (iv) impossible.

We explained the experiment and how to stop it to all of the subjects, and obtained consent to participate from all of them. In the experiment, we wanted to simulate the eye level of evacuees in a full-scale tunnel fire, which we estimated to be a height of 1.5 m. Therefore, the subjects’ eye level for the large-scale model tunnel was a height of 0.3 m.

4. EXPERIMENTAL RESULTS AND CONSIDERATIONS

Figure 3 shows pictures taken in the tunnel at 60 s, 90 s and 180 s after ignition. The pictures were photographed at a height of \(z = 0.3\) m corresponding to a full-scale height of 1.5 m, from the opposite direction of the point where the fire was started. The left-hand picture is case A while the right is case B. The pictures taken at 60 s in both cases show that the smoke has reached the ceiling at \(x = 21\) m. In case A, the ceiling lights were covered by thick smoke of \(C_s\) density = 0.6 m\(^{-1}\). Figure 4 shows the smoke distribution in the \(z\) direction at \(x = 18\) m corresponding to the times in Fig. 3. The smoke distribution at \(x = 18\) m was the closest value to the smoke density observed and recorded optically by the subjects. All the values of the smoke distribution were converted to full scale. This figure shows that in case A the smoke remained stratified and arrived at \(x = 18\) m. In case B, although the smoke was thinner in Fig. 4 (ii), the results were similar. However, in case B the ceiling lights could still be observed.

The picture at 90 s in case A shows that the ceiling lights of the tunnel were obscured by smoke and the area around the subjects was very dark. Figure 4 for case A and case B shows that the height of the smoke was lower than that at 60 s, but the smoke was still stratified at
$x = 18$ m. We could only faintly see the exit in this case. In case B, the area around the subjects was still visible, the lights were slightly covered by the smoke.

The picture at 180 s in case A shows that the closest lights close to the exit, which were installed at $x = 37$ m, $z = 0.3$ m and 0.5 m, were completely covered by thick smoke. This is because the thick smoke descended from the ceiling to the floor in the tunnel at a point far from the fire source, and then curled under the stratified thermal fume layer toward the fire source. Figure 4 for case A shows the same behavior. The picture at 180 s in case B shows that it was hard to see the lights closest to the exit, which were installed at $x = 37$ m and $z = 0.5$ m, for the same reason as in case A. Furthermore, Fig. 4 for case B shows that the thin smoke also curled back under the stratified thermal fume layer toward the fire source.

![Pictures](image)

(i) case A, 60 s  (ii) case B, 60 sec
(iii) case A, 90 s  (iv) case B, 90 sec
(v) case A, 180 s  (vi) case B, 180 sec

**Figure 3:** Pictures at $x = 21$ m, $z = 0.3$ m
To examine the influence of the physical factors upon the psychological factors, we compared the results of the tunnel fire experiments with the results of the questionnaire given to the subjects. Smoke diffusion was defined as the situation when smoke descended below eye level ($z = 0.3$ m) and spread through the tunnel.

Figure 5 shows the questionnaire results of all of the subjects, which were filled in between 40 and 60 s (before the smoke arrived at $x = 21$ m), between 125 and 145 s (when the smoke was stratified) and between 230 and 240 s (when the smoke diffused). Before the smoke arrived at $x = 21$ m, it was found that all of the subjects thought that evacuation was possible or probably possible in cases A and B. When the smoke was stratified, the number of subjects who thought it was impossible to evacuate increased compared to the previous situation.

During smoke diffusion, it was found that almost all of the subjects thought that evacuation in the tunnel fire was impossible in case A. Therefore, almost of the subjects thought that evacuation was impossible when $C_s = 0.37$ m$^{-1}$. Furthermore, in case B, it was found that 80% of all of the subjects thought that evacuation was impossible when $C_s = 0.10$ m$^{-1}$. Hence, in the case of smoke diffusion, it was found that almost all of the subjects thought that evacuation was impossible, even if the smoke density in the tunnel fire was low.
The experiment thus revealed that the subjects considered that evacuation in the tunnel fire was possible in the stratified smoke and impossible during the smoke diffusion.

5. CONCLUSIONS

The main results of this study are summarized as follows.

1. When the smoke is stratified, 80% of all of the subjects thought that evacuation was possible or probably possible.
2. No one thought that evacuation was impossible during smoke diffusion of $C_s = 0.37$ m$^{-1}$.
3. 80% of all of the subjects thought that evacuation was impossible or probably impossible during smoke diffusion of $C_s = 0.10$ m$^{-1}$.
4. In the case of smoke diffusion, almost all of the subjects thought that evacuation was impossible, even if the smoke density in a tunnel fire was low.

Thus, when investigating evacuation in tunnels, we must consider the differences between stratified and diffusing smoke.

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**Figure 5:** Results of the questionnaire

![Results of the questionnaire](chart.png)
REFERENCES

