Suggestion of estimation method of smoke generation rate by CFD simulation and fire experiments in full-scale tunnels

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Abstract

The present study clarified the smoke generation rate in a tunnel fire, which is essential data for the planning of emergency measures. The smoke generation rate was determined by the least squares method using the results of full-scale tunnel fire experiments and three-dimensional CFD simulation. The following results were obtained. The smoke generation rate per unit area increases gradually with pool fire area, 3.12 to 4.35 g/(s·m²) in the case of 1 m², 4.18 to 5.85 g/(s·m²) in the case of 4 m². When pool fire area becomes 9 m², the smoke generation rate per unit area increases rapidly to 10.1 g/(s·m²). The smoke yield by gasoline reducing rate in the case of a gasoline pan fire with an area of 4 m² is approximately 4.4 - 6.8 % and reaches around 11 % when the area increases to 9 m². The heat release rate and smoke generation rate in the case of a large bus fire is nearly equal to a gasoline pan fire of 9 m².

Key words: Tunnel fire safety, Smoke generation rate, CFD simulation, Full-scale tunnel experiment

1. Introduction

When fire breaks out in a tunnel, a small accident can easily escalate into a large one that causes loss of life. Hence, to ensure the safety of road traffic networks, specific measures against tunnel fires are needed. It is especially important to comprehend thermal layer and smoke behavior in tunnel fires for accurate disaster prevention methods. For this objective, many researches have been done in which fire experiments using full-scale tunnels or model-scale tunnels, and numerical simulations were conducted. Numerical simulation, which allows desktop analysis testing various kinds of tunnel shapes and fire scenarios, can be a general tool to investigate tunnel fire safety.

For the fire source in simulations and experiments, heat release rate [W] is used as a criterion. This value indicates the heat capacity per unit time [J/s] from burning materials. In previous studies, a general vehicle fire is approximately 3 MW and a bus fire is approximately 20 - 30 MW. Criterion for evacuation possibility depends on smoke density (Dobashi, et al., 2000), so that estimation of smoke generation rate is extremely important. However, there are few measurement of smoke generation rate in past tunnel fire experiments.

One of the methods for measuring the smoke generation rate of vehicle fires is by cone calorimeter (Briggs, 1993). In this method, which is generally used for small fires, the smoke from the fire is sucked into the chamber and the smoke particles are analyzed; that is, the smoke generation rate is measured when enough oxygen is supplied. Meanwhile, a tunnel fire caused by burning vehicles is large but the space is small, possibly causing insufficient oxygen supply. It is therefore inappropriate method to investigate a tunnel fire.

In the present study, we have developed the estimation method of the smoke generation rate, which determines the
rate by least-squares method using the results of the 3D simulation and the experiments in the full-scale tunnels. The full scale tunnel fire experiments referenced here are those at the No. 3 Shimizu Tunnel on the New Tomei Expressway (Shimoda, 2002) conducted from February 26 to March 8 in 2001, and the Higashiyama Tunnel on the Higashiyama line on the Nagoya Expressway from February 17 to 20 in 2003 (Nagoya Expressway Public Corporation, 2003; Ejiri, et al., 2004).

2. Nomenclature

\(x, y, z\): The origin of the Cartesian coordinate system is located at the fire source, \(x\) is the tunnel longitudinal axis, \(y\) is the transverse axis, and \(z\) is the vertical axis (\(z = 0\) is the floor). [m]

\(C_s\): Optical smoke density (Cs density) \([m^{-1}]\)

\(S_{\text{max}}\): Maximum smoke generation rate \([g/s]\)

\(m\): Smoke mass density \([g/m^3]\)

\(m_{\text{c}}\): Experimentally derived smoke mass density converted from optical smoke density \([g/m^3]\)

\(m_{n}\): Numerically derived smoke mass density with normalized smoke generation rate \([g/m^3]\)

\(A\): Pool fire area \([m^2]\)

\(Q_{\text{max}}\): Maximum convective heat release rate \([MW]\)

\(\beta\): Smoke yield = \(S_{\text{max}} / \) Maximum fuel reducing rate [-]

\(t\): Elapsed time from ignition [s]

3. Outline of fire experiments in the full-scale tunnels

The No. 3 Shimizu Tunnel has a length of 1119 m, a height of 8.5 m, a large cross-sectional area (115 m\(^2\)), with 2 % gradient from the west to the east portal and a longitudinal ventilation system. Figure 1 shows an outline of the test tunnel. The following sizes of gasoline pool fire were examined: 1 m\(^2\) source area (1g0 case), 4 m\(^2\) source area (4g2, 4g5 cases), 9 m\(^2\) source area (9g2) and large bus fire (ib2) in the experiment.

The Higashiyama Tunnel has a length of 3560 m, a height of 4.7 m, a cross-sectional area of 48 m\(^2\), and a transverse ventilation system. The gradient shifts from 1.10 % to -0.47 % at \(x = 160\) m. Figure 2 shows an outline of the test tunnel. The following sizes of gasoline pool fire were examined: 1 m\(^2\) source area and 4 m\(^2\) source area. In total, five fire experiments in the No. 3 Shimizu Tunnel and eight in the Higashiyama Tunnel were suitable for the present study.

Table 1 shows the experimental cases in each tunnels. The size of gasoline pool fire, longitudinal velocity and exhaust volume are denoted as follows: 1g0 in the No. 3 Shimizu Tunnel means a gasoline pool fire with a 1 m\(^2\) source area and longitudinal ventilation velocity of 0 m/s. 1g05-0 in the Higashiyama Tunnel means a gasoline pool fire with a 1 m\(^2\) source area, longitudinal ventilation velocity of 0.5 m/s and exhaust volume of 0 m\(^3\)/s. Additionally, the suffix -0 in the Higashiyama Tunnel means 0H, exhaust volume 0 m\(^3\)/s; -1 means 1H, exhaust volume 136 m\(^3\)/s; and -2 means 2H, exhaust volume 238 m\(^3\)/s. In the No. 3 Shimizu Tunnel, the large bus fire experiment (ib2) was examined. In the cases of 9g2 and ib2 in the No. 3 Shimizu Tunnel and 4g2-2(2) in the Higashiyama Tunnel, the operation of the water-suppression system was started in the middle of experiments. However, the present study focused on the period prior to the operation of the water-suppression system.

![Fig. 1 Schematic diagram of the No. 3 Shimizu Tunnel. This tunnel has a length of 1119 m, a height of 8.5 m, a large cross-sectional area (115 m\(^2\)), and a longitudinal ventilation system. Fire source is settled at 462 m from the west portal, this point is origin.](image-url)
4. Simulation Method

Highly quantitative 3D CFD analysis using “Fireles,” a large eddy simulation (LES) turbulence model, was applied for the present study tunnel (Ejiri, et al., 2004; Kunikane, et al., 2002; Kunikane, et al., 2003; Wang, et al., 1998; Wang, et al., 2000). The governing equation consists of the continuity equation, Navier-Stokes equation, energy equation, and advection-diffusion equation of smoke mass density.

Since the temperature variation is much less than that of the velocity, the 3D LES turbulence model combining the Smagorinsky model is applied only to the momentum equation. The explicit Crank-Nicolson method is used for the time lapse, and the SMAC method is used for establishing the pressure and velocity field. The fourth-order accuracy central-difference scheme is used to describe the convection term of the momentum equations, while the third-order accuracy upwind-difference scheme is used for the convection term of the energy equations. The adjustable time step method is employed for computation that satisfies the Courant condition. The heat transfer to the tunnel wall is calculated by a one-dimensional heat conduction equation for each cell, using finer grids in solid side. It has been confirmed that the results derived by the simulation method were in good coincidence with the experimental results in the No. 3 Shimizu Tunnel and the Higashiyama Tunnel as for the velocity and temperature distribution.

Table 1  Experimental case

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<td>1H (136 m$^3$/s)</td>
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<td>0.5</td>
<td>2H (238 m$^3$/s)</td>
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<td>2.0</td>
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</table>

Fig. 2  Schematic diagram of the Higashiyama Tunnel. This tunnel has a length of 3560 m, a height of 4.7 m, a cross-sectional area of 48 m$^2$, and a transverse ventilation system. The origin is fire source. The gradient shifts from 1.10% to -0.47% at $x = 160$ m. Longitudinal ventilation was occurred by a small arrow in the figure. The white rectangular is exhaust point and the gray square is supply point.
5. Derivation of heat release rate

The heat release rate is defined in the same manner as the previous report (Kunikane, et al., 2003), where it was estimated using the measured data such as (1) the gasoline mass consumption rate by load cells, (2) the temperature rise of the ceiling near the fire source and (3) the radiation heat from the fire source. The results of temperature rise in the tunnel obtained from the numerical simulations using the estimated heat release rate agreed well with those in the experiments. The heat release rate curves for the 1 m² gasoline pool fire in the Higashiyama Tunnel were determined by calculation of heat radiation curve by measuring the heat radiation from the fire and gasoline reducing amount per unit heat radiation. The heat release rate curve for the 4 m² gasoline pool fire, on the other hand, was determined by calculating the heat release rate from the measured maximum temperature at some point near the fire, because the heat radiation could not be accurately measured due to excessive smoke.

Figure 3 shows time profile of the theoretical total heat release rate in the case of 1g2-0 in the Higashiyama Tunnel. The black line denotes the result derived from the radiated heat measured in the experiment. A red line was the approximate polyline, the heat release rate distribution differs from the experiments at points immediately after the ignition (t = 0 s) and before extinguishing (t = 660 s). These two points of after the ignition and before extinguishing were determined as follows. In the experiments, the heat should be released at a certain rate immediately after ignition, while the measured temperature and radiated heat increased gradually. Therefore, the heat release rate at the ignition was determined by extrapolation of the radiation heat curve after 60 s. And these measured values did not decrease to zero after the fire was extinguished due to heat radiating from the walls and the floor. Hence an extinguishment time, when heat release rate reduced to 0 MW, was determined from the image captured by the video camera. Thus, theoretical total of heat release rate assuming perfect combustion can be determined, in the case of gasoline pool fire convective component as thermal fumes, which is convective heat release rate, is reported as 50 % of the theoretical total of heat release rate by the previous report (Kunikane, et al., 2003). Therefore 50 % of the theoretical total of heat release rate were defined as the convective heat release rate used in the simulation. Thus, the maximum values of the convective heat release rate in the No. 3 Shimizu Tunnel and the Higashiyama Tunnel are shown in Table 2 and 3.

6. Derivation of smoke generation rate

6.1 Conversion of smoke particle mass density to optical smoke density

Concentration of smoke (Cs), which is a type of optical smoke density generally used in studies on tunnel fires, was used to measure smoke density. Cs density was averaged based on the tunnel width and was calculated as an extinction coefficient in the Lambert-Beer equation as follows:

![Fig. 3](image-url)
where $I$ is the intensity of incident light, $I_0$ is the intensity of transmitted light (non-smoke), and $l$ is the distance traveled by light through the gas. In the simulator, the mass density of smoke particles $m$ [g/m$^3$] was calculated using the convective diffusion equation. Therefore, a comparison between mass density of smoke particles $m$ and optical smoke density must show good correlation.

In the case of n-heptane as the fuel, the relation between $C_s$ at low density (1 m$^{-1}$ or below) and $m$ is substantially linear; a factor of proportionality of 7 - 18 has been reported (The Illuminating Engineering Institute of Japan). Additionally, Takao et al. (Takao, et al., 2004) reported that in combustion experiments, in which the fuel was kerosene and light oil, the relationship was not substantially linear at high density (above 2 m$^{-1}$); the $C_s$ growth rate decreased gradually with increasing $m$. However, the experimental formula uses ln $m$, and the relationship at low density indicates that $C_s$ becomes 0 when $m$ is 0.

$$C_s = \begin{cases} 11.1m & m \leq 0.15 \text{ g/m}^3 \\ 1.73 \ln m + 4.94 & m > 0.15 \text{ g/m}^3 \end{cases}$$

The coefficient in the first expression in Eq. (2), 11.1, was determined to be the slope of the curve for the second expression of Eq. (2) at $m = 0.15$ (see Fig. 4). It is possible that this relation depends on the characteristics of products of combustion such as smoke particle sizes. However, the above relation was used in the present study, because of lacking knowledge regarding the relation in case of gasoline, and with assumption that there is no significant difference in smoke particle density.

![Fig. 4 This figure shows relation between smoke particle mass density $m$ and optical smoke density $C_s$ defined by Eq. (2). When the smoke density $m$ is lower than 0.15 g/m$^3$ (circle), the linear relationship of Eq. (2) was applied. Otherwise, the experimental logarithmic formula of Eq. (2) was used in the present study.](image)

### 6.2 Method of determining the smoke generation rate

Measurement of smoke generation rate in large-scale fire experiments is difficult, so that smoke generation rate curve in the present study was determined in the shape same as the heat release rate in Figure 5, as with the previous report (Kunikane, et al., 2003). In the simulation of fire experiments, velocity, pressure and temperature must be calculated simultaneously due to interaction among each other, meanwhile smoke density field does not influence to other variables, that is, the relation becomes 1-way. Additionally, advection-diffusion equation of smoke mass density is linear, that is, when Dirichlet boundary conditions and Neumann boundary conditions are zero, and smoke mass density is proportional to smoke generation rate which is the source term in the equation. Hence, when a smoke mass density $m_1$ can be obtained with a smoke generation rate $S_1$, and if the curve shape of smoke generation rate is the same, the smoke mass density $m_2$ can be obtained with the smoke generation rate $S_2$ as following relation.

$$m_2 = m_1 \cdot S_2 / S_1$$

Using this relation, once a smoke mass density $m_0$ was determined with a given smoke generation rate curve which
has the maximum value of unity, smoke mass density $m$ with an arbitrary smoke generation rate $S_{\text{max}}$ can be obtained by the following relation.

$$m = m_0 \cdot S_{\text{max}}$$  \hspace{1cm} (3)

There are few measurements of smoke generation rate by methods except the use of cone calorimeter. In the present study, maximum smoke generation rate $S_{\text{max}}$ was determined by the least squares method, minimizing deviations between smoke density by the simulation and optical density of experimental results. The average value for 60 s was calculated in the simulation and the measured optical density were converted to the mass density distribution $m_e$ [g/m$^3$] by Eq. (2), where the suffix $i$ indicates a measuring location. Mass density distribution $m_e$ [g/m$^3$] at $S_{\text{max}}$, are related as follows:

$$m_i \approx m_i(= m_0 \cdot S_{\text{max}})$$  \hspace{1cm} (4)

The total squared differences between experiments $m_i$ and simulation $m_i$ designated by $G$ are given by:

$$G = \sum_{i=1}^{N} (m_i - m_{i,j})^2$$  \hspace{1cm} (5)

Substituting Eq. (4) for Eq. (5), the following relationship is obtained:

$$G = \sum_{i=1}^{N} (S_{\text{max}} \cdot m_{0,i} - m_{i,j})^2$$  \hspace{1cm} (6)

$S_{\text{max}}$ minimizing $G$, that is, the point of $\partial G/\partial S_{\text{max}} = 0$, is found by Eq. (6). Hence, $S_{\text{max}}$ is given by:

$$S_{\text{max}} = \frac{\sum_{i=1}^{N} (m_{0,i} \cdot m_{i,j})}{\sum_{i=1}^{N} m_{i,j}^2}$$  \hspace{1cm} (7)

In the fire experiments in the No. 3 Shimizu Tunnel, the longitudinal measuring points were located at $x = -150, -100$, and -50 m on the upstream side from the fire and $x = 10, 20, 50, 100, 150, 200, 300, 400, 500, 500$ and 600 m downstream from the fire. The vertical measuring points were located at $z = 1.5, 4.5, 8.0$ m on the upstream side and $z = 1.5, 3.0, 4.5, 6.0, 7.0, 8.0$ m downstream. The total was 57 points and the $Cs$ values were determined by optical smoke density measurements. However, with regard to the fire experiments of the 1 m$^2$ fire pan, the total number of measuring points was 33 due to measuring only up to $x = 150$ m downstream from the fire. Due to the down grade to upstream of the fire source, backlayering to the upstream seldom occurred, therefore, smoke density measured at upstream of the fire source had not been used in the present study. At the location being far from the fire source to the downstream side, smoke arrives late, so that the variation of smoke density is delayed against that of smoke generation rate. Additionally, at the location being closer to the fire source, the variation of smoke density occurred by the fire source. Hence smoke density at $x = 50$ m and 100 m close to the fire source except $x = 10$ m and 20 m and equal or larger than 0.1 m$^{-1}$ was used. The maximum smoke generation rate $S_{\text{max}}$ determined from the simulation and these experimental measurement results using the least squares method is shown in Table 2. The table also shows the maximum convective heat release rate $Q_{\text{max}}$ [MW], in which the fuel combustion is perfect, maximum smoke generation rate $S_{\text{max}}$ [g/s] and smoke yield $\beta = S_{\text{max}}$/maximum gasoline reducing rate.

In the fire experiments in the Higashiyama Tunnel, the longitudinal measuring points were located at $x = -50$ m on the upstream side from the fire and $x = 50, 100, 200$ m downstream from the fire. The vertical measuring points were located at $z = 1.5, 3.0, 4.5$ m on the upstream and downstream sides. The total number was 12 points and the $Cs$ values were determined by optical smoke density measurements. In the Higashiyama Tunnel experiments, the gasoline pool fires were small, which were only 1 m$^2$ and 4 m$^2$, smoke density did not become thick as the No. 3 Shimizu Tunnel, furthermore, measuring points were limited, $S_{\text{max}}$ determined from the simulation and these experimental measurement results removing a point of $Cs = 0$ m$^{-1}$ using the least squares method is shown in Table 3.
Thus, simulation results used the determined smoke mass generation rate and experimental results are shown in Figs. 6 and 7, which are 4g2 in the No. 3 Shimizu Tunnel and 1g05-0 in the Higashiyama Tunnel respectively. In the No. 3 Shimizu Tunnel, the longitudinal velocity and temperature distributions had been confirmed by the past report (Kunikane, et al., 2002, 2003); therefore, vertical (z) distributions of smoke density at x = 50 m, 100 m and 150 m are shown in Fig. 6. It can be seen that experimental results and simulation results have good correspondence. In the Higashiyama Tunnel, because longitudinal velocity and temperature distribution has not been confirmed, vertical profile of longitudinal velocity, temperature and smoke density at x = -50 m are shown in Fig. 7. These figures show that experimental results and simulation results have good correspondence, hence the estimated heat release rate and smoke generation rate curves can be represented almost the actual phenomenon.

Table 2  Smoke generation ratio and rate
(the No. 3 Shimizu Tunnel )

<table>
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<tr>
<th>Case</th>
<th>$Q_{\text{max}}$ [MW]</th>
<th>$Q_{\text{max}} / A$ [MW/m$^2$]</th>
<th>$S_{\text{max}}$ [g/s]</th>
<th>$S_{\text{max}} / A$ [g/(s·m$^2$)]</th>
<th>$\beta$</th>
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<tr>
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Table 3  Smoke generation ratio and rate
(the Higashiyama Tunnel )

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<thead>
<tr>
<th>Case</th>
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<th>$Q_{\text{max}} / A$ [MW/m$^2$]</th>
<th>$S_{\text{max}}$ [g/s]</th>
<th>$S_{\text{max}} / A$ [g/(s·m$^2$)]</th>
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Fig. 5 Convective heat release rate $Q_{\text{max}}$ and normalized smoke generation rate which have the same shape in the case of 1g2-0 are plotted on the left and the right vertical axis, respectively.
7. Smoke generation rate in the full-scale tunnel experiments

Figure 8 shows the maximum convective heat release rate $Q_{\text{max}}$ per unit area, and Fig. 9 shows the maximum smoke generation rate $S_{\text{max}}$ per unit area. The horizontal axis in both figures indicates the pool fire area. It can be seen that the convective heat release rate per unit area increases a little while pool fire area increases from 1 m$^2$ to 4 m$^2$, but remains constant while pool fire area increases from 4 m$^2$ to 9 m$^2$ in Fig. 8. Meanwhile, the results in the Higashiyama Tunnel have large dispersion possibly because transverse ventilation system is installed in the Higashiyama Tunnel and exhaust flow rate from the ceiling changed in three ways. Amount of increase of the convective heat release rate per unit area is large when pool fire area becomes large. The amount increased by 20 - 30% from 1 m$^2$ to 4 m$^2$, while it increased doubled from 4 m$^2$ to 9 m$^2$. Regarding smoke generation rate, there are few differences between the No. 3 Shimizu Tunnel and the Higashiyama Tunnel.

The convective heat release rate per unit area in the No. 3 Shimizu Tunnel becomes 1.40 MW/m$^2$ in the case of 1 m$^2$, 1.75 - 1.90 MW/m$^2$ in the case of 4 m$^2$ and 1.96 MW/m$^2$ in the case of 9 m$^2$. In the Higashiyama Tunnel, the convective heat release rate per unit area becomes 1.60 - 2.00 MW/m$^2$ in the case of 1 m$^2$, and 1.75 - 2.09 MW/m$^2$ in the case of 4 m$^2$.

Additionally, the smoke generation rate per unit area in the No. 3 Shimizu Tunnel becomes 3.93 g/(s m$^2$) in the case of 1 m$^2$, 5.49 - 5.85 g/(s m$^2$) in the case of 4 m$^2$ and 10.1 g/(s m$^2$) in the case of 9 m$^2$. In the Higashiyama Tunnel, the smoke generation rate per unit area becomes 3.12 - 4.35 g/(s m$^2$) in the case of 1 m$^2$, and 4.18 - 4.47 g/(s m$^2$) in the case of 4 m$^2$. In the case of pool fire area being small (1 m$^2$ and 4 m$^2$), the oxygen supply is supposed to be enough, so that
the calorific value is proportional to gasoline consumption rate. Contrarily, if pool fire area becomes large (9 m²), shortage of oxygen supply is supposed to be occurred.

In the bus fire experiment previously conducted in the No. 3 Shimizu Tunnel, because the firefighting had been done by fire brigade before fire growing maximum, ib2 was unsteady fire. Therefore, the heat release rate curve was estimated based on the temperature rise along the ceiling above the fire when the fire reached almost the maximum, and the maximum smoke generation rate $S_{\text{max}}$ were obtained in the same way (Kunikane, et al., 2002). The results in ib2 are shown in Table 2. $Q_{\text{max}} = 17$ MW and $S_{\text{max}} = 95.6$ g/s were obtained for ib2, that is, the results are close to those for a 9 m² pool fire.

In the case of gasoline pool fires, the smoke yield $\beta$ is defined as the ratio of generated smoke particle mass to combusting mass of gasoline. In the present study, both the smoke generation rate and the reducing rate of gasoline were assumed to be proportional to the heat release rate, so that $\beta$ was always constant for each case.

There are the past studies regarding smoke yield, which is ratio between smoke mass generation rate and fuel mass reducing rate in pool fire. For the calculation of smoke yield $\beta$, it was supposed that fuel mass reducing rate and heat release rate curves became same shape. The present results (red) and the past reports' results of crude oil (blue) are shown in Fig. 10. The past reports' results are burning experiments of circular pool fire in spaces (Evans, et al., 1992; Koseki and Mulholland, 1991; Mulholland, et al, 1996; Walton, et al., 1994). In the case of crude oil, $\beta$ in the case of 0.28 m² small pool fires is 5.6 - 8.3 %, $\beta$ in the case of 0.79 m² is 5.6 - 11 %, is distributed in wide range. $\beta$ in the case of pool
fire area being further large is more than 12 %. In the No. 3 Shimizu Tunnel (red triangles), $\beta$ in the cases of the 1 m$^2$ and 4 m$^2$ fire pan is almost 6.7 %; however, in the case of the 9 m$^2$ fire pan, $\beta$ increases drastically and exceeds 11 %, that is, closer to the large scale crude oil fire source. Although the No. 3 Shimizu Tunnel has cross section twice as large as the general two lane tunnels, shortage of oxygen supply may occur because of large fuel consumption rate in 9 m$^2$ pool fire area, resulting large quantity of smoke. In the Higashiyama Tunnel (red circles), $\beta$ in the cases of the 1 m$^2$ is 4.4 - 5.0 %, and 4 m$^2$ fire pan is 5.8 - 6.0 %. There are little smaller than the case of the results in the No. 3 Shimizu Tunnel. Due to the transverse ventilation system in the Higashiyama Tunnel, the oxygen supply is supposed to be enough, so that the smoke yield becomes relatively low, 4.4 - 6.0 %. Smoke yield of gasoline is lower than that of crude oil. The pan area with which smoke yield greatly rises is also larger in case of gasoline, between 4 m$^2$ and 9 m$^2$, than the area in case of crude oil, 1 m$^2$.

8. Conclusions

Smoke generation rate, which is difficult to measure, in full-scale tunnel fire experiments was suggested to estimate by least square method used measured results of smoke density and 3-D CFD simulation. Calculating of smoke generation rate in the full-scale tunnel fire experiments by this method, the main results of the present study are summarized below.

1. The smoke generation rate per unit area increases gradually with pool fire area, the smoke generation rate per unit area becomes 3.12 - 4.35 g/(s·m$^2$) in the case of 1m$^2$, 4.18 - 5.85 g/(s·m$^2$) in the case of 4 m$^2$. In the case of pool fire area being small (1 m$^2$ and 4 m$^2$), the oxygen supply is enough, so that the calorific value is proportional to gasoline consumption rate.

2. When pool fire area becomes 9 m$^2$, the smoke generation rate per unit area increases rapidly to 10.1 g/(s·m$^2$), therefore shortage of oxygen supply is occurred.

3. Smoke yield by gasoline reducing rate is in the range of 4.4 to 6.8 % for a fire size within 4 m$^2$.

4. Smoke yield by gasoline reducing rate is approximately 11 % for a fire of 9 m$^2$.

5. Heat release rate and smoke generation rate in a large bus fire are nearly the same as that for a fire of 9 m$^2$.

References


Dobashi, M., Imai, T., Yanagi, H. and Mizuno, A. and BHR Group: Numerical simulation of the emergency tunnel


