Study on Smoke Behavior in Under-viaduct Stations
by using Scale Reduced Model.

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ABSTRACT

In the event of fire at concourse of rail stations under elevated platforms, smoke may emit through stairways leading from the concourse to platforms as well as standard natural smoke discharge outlets decreed by the Building Standards Law. However there is little knowledge about smoke discharge from the concourse via the stairway. In this study, Experiments regarding smoke flow in the case of fire in concourse of rail stations below elevated platforms were carried out compare volume of smoke emitted through stairway opening with that emitted through standard natural smoke discharge outlets as decreed by the Building Standards Law, with a simple scale reduced model which stairway was placed at right angle to the concourse. As a result, in these experiments, relationship of smoke discharge between stair openings and standard natural smoke discharge outlet was found.

KEYWORDS

smoke control, stairway, model, smoke exhaustion, under-viaduct station, concourse
1. INTRODUCTION
In the event of fire in a station, appropriate smoke discharge to the outside is extremely important for safe evacuation of passengers. There are two types of smoke discharge: standard natural smoke discharge where smoke is discharged from openings and mechanical smoke discharge where smoke is discharged from openings by force using ducts and fans.

In case of fire in a station concourse of an under-viaduct station, smoke is assumed to be discharged from stairway openings as shown in Fig. 2. Such smoke discharge from stairway openings can be regarded as standard natural smoke discharge; however, stairway openings are not considered smoke outlets by the Building Standards Law (hereinafter “BSL”). Moreover, there is actually little knowledge about smoke discharge from the concourse via the stairway.

In light of this, we carried out experiments on smoke flow using a scale reduced model of rail stations under elevated platforms with a stairway at a right angle to the concourse. From the experiment results, we obtained volumes of smoke discharge from the stairway opening and standard natural smoke discharge outlets decreed by the BSL, and we evaluated the volume of smoke discharge from the stairway opening by comparing the volumes obtained.

2. PREVIOUS STUDY
We have carried out experiments on smoke flow in fire using a model of rail stations under elevated platforms with a stairway at a right angle to the concourse. The experiment results confirmed that the smoke of fire in the concourse was naturally discharged from the stairway opening to the passenger stairway, that the smoke was divided into two layers of a smoke layer and a fresh air layer, and that the smoke was discharged in the direction of the shed. From this, we can consider that experiments using that model successfully reproduced actual smoke flow.

3. EXPERIMENT OVERVIEW
In this study, we carried out experiments to evaluate the volume of smoke discharge from the stairway opening using a scale reduced model of rail stations under elevated platforms with a stairway at a right angle to the concourse as done in the past studies. From the experiment results, we sought to obtain the volume of smoke discharge from the stairway opening and from the standard natural smoke discharge outlets, and we evaluated the volume of smoke discharge from the stairway opening by comparing the

Fig.1. Image of concourse at rail stations under elevated platforms
Fig.2. Image of fire in concourse at rail stations under elevated platforms
Fig.3. Smoke flow in passenger stairway (visually observed)
Fig.4. Smoke layer in passenger stairway calculated using heat rise value
Fig.5. Verification of smoke discharge from standard natural smoke discharge outlets and stairway openings
volumes obtained.

3.1 Scaling Laws

In experiments using a model, the scaling laws need to be considered to make the behavior of the experiment subject analogous to that in the full-scale environment. In this study, we adopted a 1/10 scale model taking into account the space for the experiment and set experiment conditions to be as similar as possible in scaling laws.

Here, we determined the heat release rate, experiment time, and thermal inertia of model material as shown in the formulae 1) to 4) based on the scaling laws proposed by John H. Kloe and James A. Milke in order to make the Froude numbers of the full-scale and the scale model match.

\[
Q_m = Q_f \left( \frac{l_m}{l_f} \right)^2 \tag{1} \\
T_m = T_f \frac{l_m}{l_f} \tag{2} \\
(kpc)_{w,m} = (kpc)_{w,f} \left( \frac{l_m}{l_f} \right)^{2/3} \tag{3} \\
T_m = T_f \frac{l_m}{l_f} \tag{4}
\]

Here, \(Q\): Heat release rate [W], \(l\): Length [m], \(t\): Time [s], \(T\): Temperature [°C], \(k\): Thermal conductivity [W/mK], \(\rho\): Density [kg/m³], \(c\): Specific heat [J/kgK], \((kpc)w\): Thermal inertia [W's/m²K²], suffix \(f\): Full-scale, suffix \(m\): Scale model.

3.2 Experiment Models

For the experiments, we produced a model of a rail stations under elevated platforms with a stairway at a right angle to the concourse (Fig. 6a) and a model of a concourse with standard natural smoke discharge outlets and with no stairways (Fig. 6c, f) with an aim of evaluating the volume of smoke discharge from the standard natural smoke discharge outlets. As the objective of this experiment using models was to compare the volume of smoke discharge from standard natural smoke discharge outlets and the stairway opening, we closed both ends of the concourse, leaving the necessary air supply gaps to prevent smoke from being discharged from outlets other than the stairway opening and standard natural smoke discharge outlets.

3.2.1 Shape and Width of Stairway Ceiling

As the shape of the stairway ceiling in the models in the experiment, we adopted a stepped ceiling often used for actual stations (Fig. 6b) and a sloped ceiling (Fig. 6c) (Table 1).

As the minimum width of a station ceiling is stipulated as 1,500 mm or more by internal regulations, we produced four models with different stairway widths with the minimum being 150 mm.

Fig.6. Diagrams of models with stairway at right angle to concourse (in mm)
3.2.2 Position and Size of Standard Natural Smoke Discharge Outlets

As the models of a concourse without stairways and with standard natural smoke discharge outlets, we produced models with the standard natural smoke discharge outlet in the ceiling and a model with that on the wall as stipulated by the BSL (Table 2). Those outlets were positioned to have almost the same distance between the stairway opening and the fire source. The standard natural smoke discharge outlet in the ceiling has a square shape. The shape of that on the wall was rectangular with the vertical height of 80 mm deemed to be effective by the BSL (800 mm in full-scale environment) and positioned to be adjacent to the ceiling (Fig. 8). As the ratio the outlet area to the floor area is stipulated to be 1/50 or more by the BSL, we set five types of ratios of standard natural smoke discharge outlet area to concourse floor area greater and less than 1/50.

3.3 Expected Fire Source

As the fire source, we assumed a temporary shop stall placed in the concourse as shown in Fig. 6. The heat release rate was set to 9.49 kW in the experiment using models based on scaling laws because the heat release rate of a stall of 1,200 mm² area in the full-scale environment is 3 MW. Furthermore, the duration of the fire was set to 6 minutes 19 seconds, also based on scaling laws, assuming firefighting to begin 20 minutes after the fire breakout.

3.4 Measurement Device

In this study, we measured the temperature and pressure in the models to find the volume of smoke discharge. The temperature in the models was measured using thermocouple trees that were attached to the positions TC 1 to 9 and TS 1 to 4 as shown in Fig. 6, and thermocouple trees had thermocouple thermometers at perpendicular intervals of 30 mm.

As the pressure in the models, differences in pressure on the concourse side and on the stairs side of the stairway opening were measured using a T-shape Pitot tube pressure gauge (Fig. 9). The pressure in the stairway opening was expected to vary at the upper and lower parts of the opening because high-temperature smoke was discharged along the opening ceiling. We thus decided to measure pressure difference at six points in the perpendicular direction. On the standard natural smoke discharge outlet on the wall, we attached a pressure gauge each on the concourse side and on the outside as with the stairway opening. Pressure difference in the standard natural smoke discharge outlet in the ceiling was measured using pressure gauges attached to the center of the outlet.
4. CALCULATION OF VOLUME OF SMOKE DISCHARGE FROM OPENINGS

(1) Stairway opening

The volume of smoke discharge from the stairway opening was calculated with formulae 5), 6), 7) by applying the temperature at the opening $T_i$ and the pressure difference $\Delta p$. The experimental data was used the 60-second average of before the end of the experiment. The volume of smoke discharge from the stairway opening $m_{\text{ai}}$ was calculated by dividing into six parts in the perpendicular direction, at the point of pressure and thermocouple measurement shown in Fig.6b with the sums of those defined as the individual volumes of smoke discharge $m_i$.

$$
\rho_i = \frac{353}{(T_i+273)} \quad \delta \quad \nu_i(z) = \sqrt{\frac{2\Delta p}{\rho_i}} \quad \delta \quad m_i = \alpha p_i \nu_i A \quad \delta
$$

$v$: Flow velocity [m/s]  $\Delta p$: Pressure difference [Pa]  $\rho$: Density [kg/m³]
$m_i$: Volume of smoke discharge (Mass flow rate) [kg/s]  $A$: Area of smoke discharge outlet [m²]
$\alpha$: Flow rate coefficient 0.7  $T$: Temperature [°C]  Suffix $i$: Number of individual opening division

The BSL stipulates that openings in the upper zone 800 mm downward from the ceiling are effective for smoke discharge. We thus defined that the area effective for smoke discharge from the stairway opening to not be the whole area of the stairway opening facing to the concourse, rather that it be the product of the stairway width multiplied by the above-mentioned 80 mm (800 mm in the full-scale environment, Fig. 8).

(2) Standard natural smoke discharge outlet on the wall

The volume of smoke discharge from the standard natural smoke discharge outlet on the wall $m_{\text{ai}}$ was calculated with formulae 5), 6) and 7) as done for that from the stairway opening. The volume of smoke discharge from the standard natural smoke discharge outlet on the wall was divided into two parts in the perpendicular direction (800 mm), at the point of pressure and thermocouple measurement shown in Fig.6e with the sums of those defined as the individual volumes of smoke discharge $m_i$.

(3) Standard natural smoke discharge outlet in the ceiling

The volume of smoke discharge from the standard natural smoke discharge outlet in the ceiling was calculated with formulae 5), 6) and 7) by applying the temperature measured at the center of the outlet $T_i$ and the pressure difference $\Delta p$. (Fig.6f)

5. RESULTS AND DISCUSSION

We compared the volumes of smoke discharge measured at stairway openings and standard natural smoke discharge outlets. Fig. 10 shows the volumes of smoke discharge in the different conditions.

(1) Effect of the shape of stairway ceiling

Comparison between the volumes of smoke discharge from stairway openings with stepped ceiling and with sloped ceiling showed the volumes were almost equal to each other. Thus, we can say that the shape of the stairway ceiling does not have much effect on smoke discharge from stairway openings. Moreover, the larger the ratio of opening area was, the larger the volume of smoke discharge was.

(2) Effect of position of standard natural smoke discharge outlets

Comparison between the volumes of smoke discharge from standard natural smoke discharge outlets on the wall and in the ceiling revealed a tendency for the volume from outlets in the ceiling to be larger than that from outlets on walls. This is considered to be because the volume of smoke discharge from standard natural smoke discharge outlets in ceilings set upward of the smoke became larger as heated air raised smoke. Moreover, the larger the ratio of opening area was, the larger the volume of smoke discharge was.

(3) Comparison between volumes of smoke discharge from stairway opening and standard natural smoke discharge outlets

Comparison between the volumes of smoke discharge from stairway openings and standard natural smoke discharge outlets revealed a tendency for the volume from stairway openings to be larger than that from outlets. This is considered to be because the smoke layer in the stairway opening was lower than 80 mm downward from the ceiling (800 mm in the full-scale environment), the zone the BSL stipulates as being effective for smoke discharge, and the smoke was discharged from a further lower zone.
From this, we suppose that the part of the stairway opening lower than the zone 80 mm downward from the ceiling, which the BSL stipulates as being effective for smoke discharge, functioned as a smoke discharge outlet. As a result, the volume of smoke discharge from the stairway opening is expected to be greater than that from standard natural smoke discharge outlets if the ratio of the opening area is the same.

Further, from the temperature measurement results of the thermocouples in Fig. 6, the height of the smoke layer at each measurement point was calculated according to the He’s law. We compared the visual results with the calculation results by the He’s law and verified the validity of the calculation. The average smoke layer height in the concourse was almost the same between the case of the stairway opening and the case of the standard natural smoke discharge outlet. (Fig.11)

This experiment suggested that, when the area of the stairway opening effective for smoke discharge is the product of the stairway width and 80 mm downward from the ceiling (800 mm in the full-scale environment), the volume of smoke discharge from stairway openings with at least a 1/50 ratio of opening area will be larger than standard natural smoke discharge outlets with a 1/50 ratio of opening area required by the BSL.

6. CONCLUSIONS

We compared the volumes of smoke discharge from stairway openings and standard natural smoke discharge outlets in accordance with the BSL using models of a rail stations under elevated platforms with a stairway at a right angle to the concourse.

The models we used in the experiments in fires were of an under-viaduct station with a stairway at a right angle to the concourse only, although there are actually a variety of designs of rail stations under elevated platforms.

We are thus aware of the need to develop a method of identifying volume of smoke discharge more easily than experiments using models in order to evaluate volume of smoke discharge from stairway openings of rail stations under elevated platforms. For that method, we intend to investigate applicability of smoke flow simulation.

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