A Study of Smoke Control Systems Using Convective Flow in Underground Station Buildings

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1. INTRODUCTION

The present study proposes a new smoke control system named Passive Safety System for Underground Station Buildings. In this system, screen doors are installed on the platform in order to separate the inside of the station building from the tunnel, as well as to aid the air current control in the station building. Under these conditions, the air is discharged through solar chimneys. In addition, water mist is sprayed above the staircase entrances in order to cool the ambient air, which generates a descending air current in the staircases. The air current is then maintained in the direction of "outside air → staircase → concourse and platform → solar chimney → outside air". This system solves the problem of operation reliability and contributes to energy conservation by making use of a natural ventilation system, which reduces the air-conditioning load in summer, and secures sufficient performance for evacuation safety as a smoke control system in case of a fire (Figure 1). In adopting this system for an underground station building, it is necessary to check the boundary conditions in the building in order to ensure effective system operation. More specifically, it is necessary to explore the effects of hanging walls and chimneys for the effective prevention of smoke inflow into the staircase. In the present study, a 1/20 scale model of an actual station building was made, and a series of experiments were conducted in order to understand the conditions for preventing the smoke in the area affected by the fire from spreading to the staircase.

In addition, upon formulating the nature of smoke propagation under the ceiling, as well as the flow of the smoke after its front has reached the hanging wall, immediately after the ignition, the parameters of the smoke insulation will be derived on the basis of computing each of these smoke flow models.
2. FORMULATION OF SMOKE BEHAVIOR IN THE EARLY PHASE OF A FIRE

One of the purposes of the present study is to investigate the conditions for restricting the smoke propagation during a fire. Prior to presenting the investigation, this section formulates the smoke propagation behavior during the early phase of a fire, as well as the smoke behavior near a hanging wall after the smoke front has reached the wall.

2.1 Formulation of Smoke Propagation Behavior under the Ceiling

The nature of smoke propagation under the ceiling during a fire is defined in this section.

In Reference [1], Turner has provided a theoretical discussion regarding the behavior of high-density fluids in the case where a high-density fluid penetrates the bottom layer of a low-density fluid, by making use of hydraulic methods. In the present research, we use the relation $C_p u' = \Delta \rho gh$ between the propagation speed $u$ and the layer thickness $h$, as described in Reference [1], for estimating the propagation speed of the smoke front.

Matsushita et al. have proposed a prediction relation for the smoke front propagation speed within a horizontally long space, and have compared the computational results with the experimental ones. Reference [2] considers the case where constant-temperature smoke inflows from the upper part of a horizontally long compartment, and therefore it is not applicable in the case of non-stationary fire sources. As a result, it cannot be used in its original form. Furthermore, although it is assumed in Reference [2] that the propagation speed of the smoke front has a heightwise distribution, this concept is not used in the present research since it differs from the view of Turner, who assumes a constant speed for the vertical influx layer. However, it is considered that the change of the smoke temperature due to the transfer of heat from the smoke layer to the wall, as well as the calculational methods regarding each time step, can also be applied in the present section without any modifications.

The present section attempts to improve the model proposed by Matsushita et al. in order to be able to predict the smoke propagation in case of a fire within a horizontally...
long space (The propagation speed of the smoke front is estimated using the equation derived by Turner).

The smoke propagation model is based on the following assumptions:

1) The density of the smoke layer is uniform at each time step, and the layer thickness is uniform between the smoke front and its main part.

2) The propagation speed \( u_{st} \) of the smoke layer is uniform in vertical direction. Additionally, the relation between \( u_{st} \) and the hydrostatic pressure difference \( \Delta \rho gh_{st} \) at the phase boundary between the layer of smoke and the layer of air can be expressed as Equation 1 by using the proportion constant \( C_1 \). In the present research, the propagation speed of the front can be estimated from the thickness of the smoke layer and its temperature, by taking the internal Froude number \( (F_{ni} = u_{st}/(g'h_{ni})\sqrt{t}) = 1/C_1^1 \) at the front of the smoke layer as constant. \( C_1 \) has been chosen such that the experimental results for the propagation speed of the smoke front match the computational results.

\[
C_1 \rho u_{st}^2 = \Delta \rho gh_{st} \quad (1)
\]

From the energy conservation equation (Equation 2) and the mass conservation equation (Equation 3) for the smoke layer, an equation for the average temperature change of the smoke layer can be obtained (Equation 4), considering the heat loss to the walls. Heat exchange by radiation is not considered in Equation 2.

\[
\frac{d(C_{n} \rho u_{st} T_{ni})}{dt} = C_1 \rho A_{ni} (T_0 - T_{wa}) \quad (2)
\]

\[
\frac{d(\rho u_{st})}{dt} = \rho A_{ni} \quad (3)
\]

\[
C_1 \rho u_{st} \frac{dT_{ni}}{dt} = C_1 \rho A_{ni} (T_0 - T_{wa}) - \alpha A_{ni} (T_{ni} - T_{wa}) \quad (4)
\]

The temperature variations of the wall adjacent to the smoke layer have been considered in the calculations. By dividing the inside of the wall as shown in Figure 2 and setting the temperatures of the laboratory and the smoke layer as the boundary conditions, the temperature at the center of each compartment at each time step was computed based on the unsteady heat conduction calculation (Equation 5). The temperature of each compartment is considered to be equal to the temperature of the center point of the respective compartment. Furthermore, by taking the convection heat transfer from the smoke layer to the wall as equal to the heat transfer within the domain of thickness \( 2\Delta x \) locked within distance \( \Delta x \) from the wall surface in the direction of both the smoke and the inside of the wall, and regarded comprising a wall, the temperature of the wall surface is computed from Equations 6 and 7.
Temperature in the wall
\[ c_p \rho \Delta x (T_{wi,i+1} - T_{wi,i}) = \left( \lambda_w \frac{T_{wi-1,i} - T_{wi,i}}{\Delta x} \right) - \left( \lambda_w \frac{T_{wi,i} - T_{wi+1,i}}{\Delta x} \right) \]
\[ \Leftrightarrow T_{wi,i+1} = \left( \frac{\lambda_w \Delta t}{c_p \rho \Delta x^2} \right) (T_{wi-1,i} - 2T_{wi,i} + T_{wi+1,i}) + T_{wi,i} \]  
(5)

Temperature of the wall surface
\[ \lambda_w \frac{T_{as,i} - T_{w,i}}{2 \Delta x} = \alpha (T_{as,i} - T_{as,i-1}) \Leftrightarrow T_{as,i} = - \frac{\lambda_w}{2 \alpha \Delta x} \left( T_{as,i} - T_{w,i} \right) \]  
(6)

\[ \lambda_w \frac{T_{air,i} - T_{as,i}}{2 \Delta x} = \alpha (T_{air,i} - T_{as,i-1}) \Leftrightarrow T_{air,i} = - \frac{\lambda_w}{2 \alpha \Delta x} \left( T_{air,i} - T_{as,i} \right) \]  
(7)

Where 1 \leq i \leq 4

The calculation of the smoke behavior is compared with the experimental values in Section 3. Hence, the conditions shown in Figure 3 were set as the initial conditions for the calculation.

Regarding the smoke propagation model proposed in this paper, although there is no significant difference in the calculated values of the temperature, the thickness and the propagation speed of the smoke layer even in the case where the smoke layer thickness has been given a value which is different from the initially set value \( h_{0,0} \), it is desirable for the values to be as realistic as possible. The initial value for the thickness of the smoke layer in the present research has been taken as the computational output after performing a steady calculation with regard to the area illustrated in Figure 4. Although this calculation does not take into account the heat transfer from the smoke to the wall, it is possible to set the distance between the central axis of the fire source and the fire front (i.e., the length of the area corresponding to this calculation) to an arbitrary value.
At each time step, the transition of the average smoke layer temperature is calculated from Equation 4, and the transition of the distance from the central axis of the fire source to the smoke front is calculated by sequentially adding the distance travelled \( (u_{s1} \times \text{time interval } \Delta t) \). In addition, the smoke layer thickness is calculated, compensating for the difference between "the mass inflow from the plume into the smoke layer" and "the mass increase in the smoke layer + the mass flow at the smoke front" (Equation 8, Figure 5).

\[
h_{s(l+1)} = \frac{\rho_{s(l)} Q_{h(l)} \cdot \Delta t - (d \cdot \rho_{s(l)} \cdot V_{s(l)} / dt \cdot \Delta t) - (u_{s(l)} \cdot \Delta t) B h_{s(l)} \rho_{s(l)}}{X_{h(l)} + (u_{s(l)} \cdot \Delta t) B h_{s(l)} \rho_{s(l)}} + h_{s(l)}
\]

Figure 3 Initial conditions of the calculation (units: mm)

Figure 4 Calculation of \( h_{s0} \)

Figure 5 Smoke propagation model in the early phase of a fire
2.2 Calculation of Heat and Mass Inflow from the Plume into the Smoke Layer

The four types of fire sources shown in Table 1 were used for the model experiments in the next section. However, since the heat release rate set for each fire source is not attained immediately after ignition, and regarding the fact that the fire sources become unsteady, the behaviour of the plume based on the heat release rate could not be used for the calculations as set. By using cone calorimeter equipment (ISO 5660), the heat release rate of each fire source was measured based on the oxygen consumption method (Figure 6). The experiment was repeated several times for each fire source setup. Since the measured values approximately matched, Figure 6 shows their mean values.

<table>
<thead>
<tr>
<th>No.</th>
<th>Fire source size (mm²)</th>
<th>Set gas flow rate (L/min)</th>
<th>Set heat release rate Q (kW)</th>
<th>Heat release rate converted into real size (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100×100</td>
<td>1.02</td>
<td>1.68</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>100×100</td>
<td>0.68</td>
<td>1.12</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>50×50</td>
<td>0.68</td>
<td>1.12</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>50×50</td>
<td>0.34</td>
<td>0.56</td>
<td>1</td>
</tr>
</tbody>
</table>

※The heat release rate was calculated with the total amount of heat from LP gas as 23,673 kcal/m³

Figure 6 Time series variation of H.R.R.

The heat and mass inflow from the plume into the smoke layer were calculated by using the average measurement of the heat release rate based on the following assumptions:

3) Air inflow from the sides is not limited since the experimental model is 750 mm in width (F.S. 15 m), which is sufficiently large for the fire source. In addition, the combustion behavior (the flame and plume behavior and the height of the virtual thermal point source) in the free space is applicable without considering the influence of the ceiling.
4) Approximately half of the mass and the heat inflow from the plume into the smoke layer \((\rho_0Q_0, C_p\rho_0Q_0T_0)\) is attributed to the smoke layer on the side of the staircase.

In performing the computation of the smoke propagation model described in section 2.1, the height \(z'\) from the virtual thermal point source to the lower edge of the smoke layer has been calculated for each time step by utilizing Equation 8. Furthermore, the outputs \(\rho_0Q_0\) and \(C_p\rho_0Q_0T_0\) for the height \(z'\) were computed and were used as input for the calculations.

2.3 Formulation of Smoke Behavior after the Smoke Front Reaches the Hanging Wall

This section formulates the smoke behavior after the smoke reaches the hanging wall. In this model, the area of the smoke layer at the time when the smoke front reaches the hanging wall is defined as the upper part of the smoke layer, while the smoke layer flowing below the upper part of the smoke layer after reaching the hanging wall is defined as the lower part of the smoke layer.

The following assumptions are added to assumptions 1) to 4) in the previous sections:

5) After the smoke front has reached the hanging wall, the thickness of the upper part of the smoke layer does not vary.

6) After the front of the lower smoke layer has returned to the location of the fire source, the lower smoke layer interleaves the fire source and outflows to the opposite side of the space at a rate of \(M_{out}\) (kg/s), as shown in Equation 9 (Figure 7).

Since passive safety systems comprise large-section solar chimneys (connected to the outside of the building) in the space opposite the staircase from the point of view of the fire source, it is assumed that the smoke on the side of the chimney does not descend at a time of fire. For this reason, Equation 9 cannot be utilized in cases where the smoke descends due to the inability of the chimney to exhaust the smoke (however, such cases were not observed during the experiments described in the next section).

\[
M_{out} = \frac{2}{3}B_s\sqrt{2g\rho_{12}(\rho_{air} - \rho_{12})} \cdot h_{x_2}^{3/2}
\]  

7) After the front of the lower layer of smoke has returned to the location of the fire source, since the plume pulls a part of the lower layer of smoke, which has higher temperature than the surrounding air, the temperature inside the plume at the level of the lower edge of the upper layer of smoke becomes higher than the temperature inside the plume in the ambient air. Then, the temperature increase at the central axis of the plume is calculated by using the prediction relation [3] proposed by Watanabe et al (Equation 10, Figure 8).

The flow velocity along the axis is not influenced by the entrainment of the lower smoke layer. Moreover, the temperature of the plume and the flow velocity along the axis follow the normal distribution in horizontal direction.
According to the above assumptions, the initial conditions shown in Figure 9 are set for calculation after the smoke layer reaches the hanging wall. The temperature increase in the upper part of the smoke layer at each time step is calculated by using Equation 13, obtained from the energy conservation equation (Equation 11) and the mass conservation equation (Equation 12). Using the temperature of the upper part and Equation 12, the mass and heat inflow from the upper part into the lower part of the smoke layer is calculated at each time step. Furthermore, the changes in the temperature \( T_{s2} \) of the lower part, the propagation velocity toward the fire source \( u_{s2} \), and the smoke layer thickness \( H_s \) are calculated on the basis of the mass and heat inflow in the same way as in the case of the smoke propagation model in Section 2.1. In the calculations, mixing between the upper part and the lower part of the smoke layer is not considered.

\[
\frac{d\left(C_p \rho_{s1} V_{s1} T_{s1}\right)}{dt} = C_p \rho_0 Q_0 T_0 - C_p \rho_{s1} Q_{s1 \rightarrow s2} T_{s1} - \alpha A_{s1} (T_{s1} - T_{a0})
\]  

(11)

\[
\frac{d\left(\rho_{s1} V_{s1}\right)}{dt} = \rho_0 Q_0 - \rho_{s1} Q_{s1 \rightarrow s2}
\]  

(12)

\[
C_p \rho_{s1} V_{s1} \frac{dT_{s1}}{dt} = C_p \rho_0 Q_0 (T_0 - T_{s1}) - \alpha A_{s1} (T_{s1} - T_{a0})
\]  

(13)
3. 1/20 SCALE MODEL EXPERIMENT

3.1 Outline of the Model Experiment

Figure 12 shows the cross section of a 1/20 scale model of an actual station building, the size of which is 200L×15W×10H m³. The location of the fire source, the diameter \(D\) of the fire source, the heat release rate \(Q\) (see Table 1 and Figure 6), the height \(H'\) of the hanging wall, the aisle width \(W'\) below the hanging wall, and the temperature rise \(\Delta T_c\) of the electric heaters in the chimney were set as parameters (Table 2). As a result, the number of experiments was large.

Table 2 Experimental conditions

<table>
<thead>
<tr>
<th>Experiment type</th>
<th>Location of fire source</th>
<th>Fire source No.</th>
<th>(H') (mm)</th>
<th>(W') (mm)</th>
<th>(\Delta T_c) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoke front velocity</td>
<td>b), c)</td>
<td>1~4</td>
<td>150</td>
<td>750</td>
<td>0, 20, 40, 60</td>
</tr>
<tr>
<td>Restriction of smoke propagation</td>
<td>a), b), c)</td>
<td>1</td>
<td>0 to 400</td>
<td>300 to 750 (150 steps)</td>
<td>0, 20, 40, 60</td>
</tr>
<tr>
<td>Pre-ignition ventilation amount</td>
<td>-</td>
<td>-</td>
<td>0, 150</td>
<td>300 to 750 (150 steps)</td>
<td>0, 20, 40, 60</td>
</tr>
</tbody>
</table>
Table 3  Experiment implemented in this chapter*

<table>
<thead>
<tr>
<th>Type of experiment</th>
<th>Outline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understanding the propagation speed of the smoke front</td>
<td>Comprehending the propagation speed of the smoke front under the ceiling by conducting an experiment, and comparing the results from the computation of the smoke propagation model. The value of the proportion constant $C_1$ is chosen such that the experimental and the calculational results match.</td>
</tr>
<tr>
<td>Success / failure of the smoke insulation</td>
<td>Understanding the conditions necessary for smoke insulation by examining whether smoke enters the staircase for each combination of the parameters.</td>
</tr>
<tr>
<td>Measuring the ventilation air volume before ignition*</td>
<td>Upon experimentally obtaining the conditions for smoke insulation, there is also a need to measure the ventilation air volume per unit time for all combinations of the parameters of the walls and the temperature of the heater inside the chimney. The calculated values are adjusted in such a way that the experimentally obtained values and the computed values match.</td>
</tr>
</tbody>
</table>

* For details about the types, methods and models of the experiments, as well as details about the installation position of the detectors, see Ref. [4]

** When deriving the parameters of the smoke insulation from the results obtained from the experiment regarding the success or failure of the hanging wall prior to the smoke entering the chimney. The measurement of ventilation air volume before ignition has the purpose of obtaining the wind speeds below the hanging wall for each experimental condition, and can be regarded as supplementary to the experiment regarding the success or failure of smoke confinement.

3.2  Experimental Results and Discussion

Figure 11 shows the experimental results for the propagation of the smoke front and the calculation results for the smoke propagation model when the fire sources given in Table 3 were used under the conditions of $\Delta T_c = 0$ (K) and fire source location b). The plot colors indicate the propagation directions of the smoke front within a single experiment (gray: toward the staircase, white: toward the chimney), and the plot types indicate the results under the same experimental conditions. $C_1$ in Equation 1 was calculated for all fire source parameters by using the least squares method.

Figure 11  Transition of smoke front position (left axis) and smoke layer thickness (right axis)
The experimentally obtained constant $C_i$ severely deviates from the interval provided in Reference [1] ($0.5 \leq C_i \leq 2.0$) in the case of fire source No.2 (Figure 11(b)). It is considered that this deviation is caused by the large differences in the input values for the mass and heat inflowing from the plume into the smoke layer, which originate from the fact that in the case of fire source No.2, the gas flow rate corresponding to the burner becomes extremely small, which disturbs the shape of the flame and the plume. For this reason, the analysis in the present research is based on the mean value $C_{i\text{ave}}$ (=1.36) of all values of $C_i$ as obtained from the three fire source setups, excepting fire source No.2.

The calculated and the experimental results were compared with respect to the smoke behavior after the smoke front has reached the hanging wall.

For fire source No. 1, where $\Delta T_c = 0$ (K) and the location of the fire source is a), the thickness of the smoke layer after it has reached the hanging wall was approximately 250 mm to 300 mm, as visible from the visualized experimental records (Figure 12). However, the computation of the smoke behavior model showed that it was approximately 200 mm (where $C_2 = C_{i\text{ave}} = 1.36$) (Figure 14). The experiment visualization clarified the mixture of smoke and air immediately after the smoke front reached the hanging wall. Since these phenomena may have greatly lowered the smoke layer, their influence should also be considered in the smoke behavior model.

In the present research, this influence is attributed to air of density $\rho_{\text{air}}$ entering the lower layer of smoke at each time step. Letting $Q_{\text{en}}$ be the volume of the air entering the lower layer of smoke, the mass conservation equation and the energy conservation equation with respect to the inside of the lower layer of smoke become

$$\frac{d (\rho_s y_{12})}{dt} = \rho_s Q_{s1\to2} + \rho_{\text{air}} Q_{\text{en}}$$  \hspace{1cm} (14)

$$\frac{d (C_p \rho_s y_{12} T_{12})}{dt} = C_p \rho_s Q_{s1\to2} T_{s1} - A_{s1} \alpha (T_{s2} - T_{\text{air}}) + C_p \rho_{\text{air}} Q_{\text{en}} T_{\text{air}}$$  \hspace{1cm} (15)

It is considered that $Q_{\text{en}}$ can be expressed as follows

$$Q_{\text{en}} = u_{\text{en}} h_{s2} B_s$$  \hspace{1cm} (16)

It is considered that the following equation gives the ratio of the velocity $u_{\text{en}}$ of the entraining air and the velocity $u_{s1\to2}$ of the smoke which flows down from the upper smoke layer to the lower smoke layer, which is regarded as being inversely proportional to the Richardson number ($Ri = \rho_{\text{air}} g h_s / (\rho_s u_{s2\to1}^2) = \|Fr^2\$), which in turn can be expressed by using the temperature $T_{s1}$ of the upper smoke layer and the thickness $h_s$ of the lower smoke layer. Here, $C_{i\text{en}}$ takes two values, namely 0.50 and 0.75.

$$u_{\text{en}} / u_{s1} = C_{i\text{en}} / Ri$$  \hspace{1cm} (17)

In the case where the inflow of air into the lower layer of smoke is considered, there is a very good match between the calculated value of the thickness of the smoke layer and
the experimental results (Figure 14).

Upon inspecting the calculated values of the thickness of the smoke layer and the experimental results for the case where fire source No. 1 is located at b) and the height of the wall between the staircase and the fire room is set to 400mm, it was found that there is a good match between the results for the thickness of the smoke layer as obtained by computing the smoke flow model and the experimental results if the air entrainment is considered (Figure 13, Figure 15).

**Figure 12** Smoke behavior after it reaches the wall (Fire source position a)) (visualized record)

**Figure 13** Smoke behavior after it reaches the wall (Fire source position b)) (visualized record)

**Figure 14** Calculated smoke layer thickness

\[(\Delta T_c = 0 \text{ (K), fire source No.1, and fire source location a)})\]

When the hanging wall height \(H'\) is smaller than the thickness \(H_s\) of the smoke layer, it is necessary to form an air current by using a chimney for the purpose of restricting the propagation of the smoke. Considering that the balance of the air current force and the smoke propagation force determines the limitation of the smoke propagation, we calculated the air current velocity below the hanging wall \(u_{\text{air}}\) which is necessary to
restrict the propagation of the smoke (Figure 15).

Since the air current grows after the smoke inflows into the chimney and assists in preventing the propagation of the smoke, $u_{\text{air}}$ was calculated up to the time when the smoke flowed into the chimney and the smoke front of the lower part came back to the location of the fire source. In the experiments, smoke inflow into the staircase was not observed even several minutes after ignition.

Air current velocity under the hanging wall which prevents the smoke from flowing into the staircase was calculated from $\rho_{\text{air}}u_{\text{air}}^2 \geq \rho_{\text{g}}gh$.

First, the restriction of smoke propagation into the staircase from the fire room under the conditions of fire source No.1 is discussed. Figure 16 shows the experimental results and the boundaries of the successful and the unsuccessful smoke restriction experiments as derived from the smoke behavior model for fire source locations a), b), and c). In the case of fire source location a), the calculated boundaries match the experimental results well when the air entrainment is considered. Under the conditions of fire source location b) and the existence of pre-ignition air current, the calculated air current velocity necessary for the restriction of the smoke propagation is larger than the experimentally derived value, which is possibly attributable to the fact that the smoke front reached the chimney before reaching the hanging wall, and a strong air current may have been generated as a result (this process is not considered in the calculation). The calculated boundaries show different tendencies before and after 100mm height of the hanging wall, owing to the temperature difference between the upper and lower parts of the smoke layer.

![Figure 16](image16.png) A conceptual diagram regarding the restriction of the propagation of smoke from the fire room into the staircase

![Figure 17](image17.png) Success / failure boundary for the smoke propagation restriction for various fire source locations
In the case of fire source location a), even when the fire source parameters are different (except for fire source No.2, where the balance between the radius of the fire source and the gas flow rate is unfavorable), there was good agreement between the experimental and the computational results due to the entrainment of air into the lower layer of smoke.

Figure 18  Success / failure boundary for the smoke propagation restriction for other fire sources

4. CONCLUSION

In the present study, we have made a prediction model of the smoke propagation behavior in the early phase of a fire, as well as of the smoke behavior after the smoke front has reached the hanging wall in a horizontally long space, and have compared the prediction results with the results from the model experiment in the section for discussion. Consequently, the following information was obtained.

By focusing on two variables, namely the propagation velocity of the smoke under the ceiling and the height of the smoke layer in the vicinity of the hanging wall after the smoke front has reached it, the two proportion constants $C_1$ and $C_{ent}$ were chosen such that the results obtained by computing the model agree with the experimental results. Furthermore, the results from computing the wind speed below the hanging wall, necessary for smoke insulation, on the basis of the temperature of the smoke layer and its thickness in the vicinity of the hanging wall, were also in good agreement with the experimental results. As a result, despite the fact that slight problems still exist with respect to the values of the proportion constants $C_1$ and $C_{ent}$, it has become possible to derive the parameters for smoke insulation for actual-size station buildings.

REFERENCES

1. J.S. Turner : BUOYANCY EFFECTS IN FLUIDS, University of Cambridge,(1973)
2. T.Matsushita and T.Wakamatsu, Mathematical model and experiments of spread of smoke front in a corridor -Horizontal spread of smoke front Part 1-, Journal of

(You can download this paper from http://www.rs.noda.tus.ac.jp/coe-fire/result/publish.html)

SYMBOLS

\( u \) : Moving velocity of the smoke tip (m/s)
\( u_{s1\rightarrow2} \) : (m/s)
\( u_{ent} \) : (m/s)
\( \rho \) : Density (kg/m\(^3\))
\( \Delta \rho \) : Density difference between the smoke layer and the ambient air (kg/m\(^3\))
\( T \) : Temperature (K)
\( \Delta T \) : Temperature rise (K)
\( \Delta T_c \) : Set temperature rise of the electric heaters in the chimney (Temperature rise from the laboratory temperature) (K)
\( Q \) : Heat release rate of the fire source (kW)
\( Q_s \) : Volumetric inflow per unit time from the plume into the smoke layer (m\(^3\)/s)
\( Q_{s1\rightarrow2} \) : Volumetric inflow per unit time from the upper part into the lower part of the smoke layer (m\(^3\)/s)
\( h_{s1} \) : Thickness of the upper part of the smoke layer (m)
\( h_{s2} \) : Thickness of the lower part of the smoke layer (m)
\( H_s \) : Thickness of the smoke layer (= \( h_{s1} \) + \( h_{s2} \) (m))
\( X_1 \) : Horizontal distance from the central axis of the fire source to the tip of the upper part of the smoke layer (m)
\( g \) : Gravitational acceleration (m/s\(^2\))
\( V \) : Volume of the smoke layer (m\(^3\))
\( A \) : Area of contact between the smoke layer and the surrounding wall (m\(^2\))
\( H' \) : Hanging wall height (mm)
\( W' \) : Aisle width under the hanging wall (mm)
\( D_f \) : Diameter of the fire source (mm)
\( \alpha \) : Convective heat transfer coefficient (=0.01745 (kW/m\(^2\)/K))
\( C_p \) : Constant-pressure specific heat (= 1.0 (kJ/kg/K))
\( z_0 \) : Virtual-point heat source height (m)
\( B_5 \) : Width of the scale model (m)
**Suffix**

$s1$: Upper part of the smoke layer  
$s2$: Lower part of the smoke layer  
$\text{air}$: Ambient air  
$0$: Plume at the height of inflow into the smoke layer  
$w$: Wall  
$w0$: Wall surface