The Movement of Smoke in Horizontal Passage under the Soffit against an Air Flow

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ABSTRACT

A system to control smoke flow at fire by providing differential pressure between rooms has frequently been adapted to many buildings. The pressurized smoke control system of a vestibule at stairwell is one of the examples. Supposing the initial stage of fire, this study is to grasp the relationship between the air velocity to prevent the smoke flow in a horizontal passage with the soffits and the properties of smoke (smoke layer temperature, smoke layer thickness and buoyancy) near the soffit.

It was concluded that the air velocity under the soffit v and $(\Delta p/\rho)^{1/2}$, and v and $(\Delta\bar{\theta}/T_s)^{1/2}$ are in proportional relationship respectively.

KEYWORDS:pressurized smoke control system, soffit, buoyancy, critical air velocity

1. INTRODUCTION

A system to control smoke flow at fire by providing differential pressure between rooms has frequently been adapted to many buildings. The pressurized smoke control system of a vestibule at stairwell is one of the examples. With this smoke control system, however, the air velocity of supplying air to obtain differential pressure is calculated by assuming the temperature inside smoke layers to be uniform, since the calculation method of smoke movement in a single layer [1] was proposed.

In addition, the effect of soffits frequently installed at the openings of practical buildings is not taken into consideration. Under the circumstance, it is considered that more adequate air velocity of supplying air can be set by clarifying the effect of soffits in relation with the temperature distribution inside a smoke layer. Supposing the initial stage of fire, this study is to grasp the relationship between the air velocity to prevent the smoke flow in a horizontal passage with the soffits and the properties of smoke (smoke layer temperature, smoke layer thickness and buoyancy) near the soffit.

2. OUTLINE OF THE EXPERIMENT

2.1 Outline of the experiment

FIGURE 1 outlines this experiment. This experiment reproduces the state where a smoke layer and an air layer are forming two layers near the soffit①. In this study, the smoke layer was defined as a portion of the air heated by an origin of plume and with a temperature higher than that immediately before the fans.

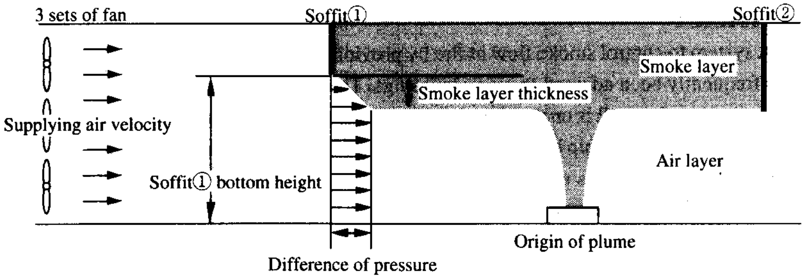


FIGURE 1 Outline of the experiment

2.2 Experimental facility

The experimental facility is outlined in **FIGURE 2**. The soffit① to limit smoke spread and the soffit② to adjust the thickness of the smoke layer were installed on the passage.The distance from the soffit①-② was determined for 7.0(m) after confirming that the smoke layer is formed near the soffit①, and the origin of plume was installed at the center between the soffit①-②. Installing 3 sets of fan which can control airflow rate, the specified air velocity was set.

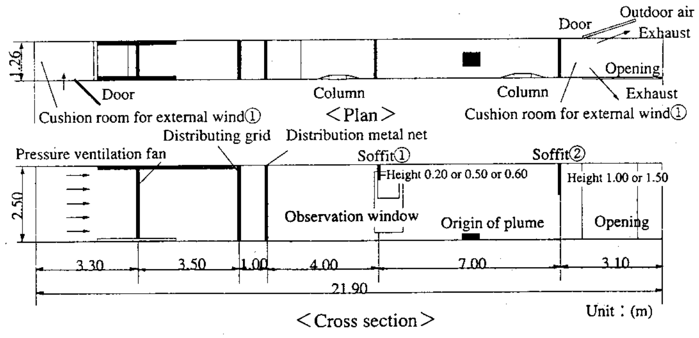


FIGURE 2 Outline of experimental facility

2.3 Measured items

The temperature and the air velocity were measured at the points shown in **FIGURE 3**.

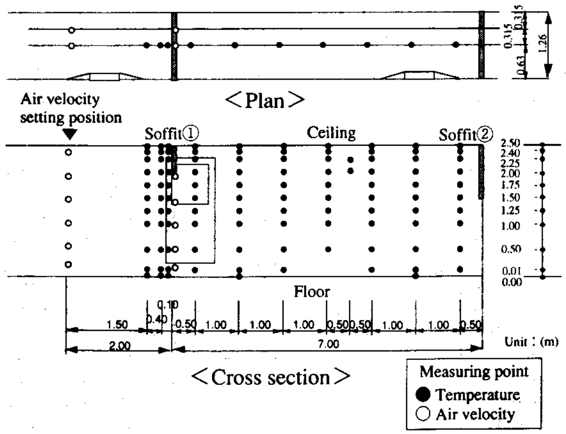


FIGURE 3 Position of mesurement points

TABLE 1 gives the equipment used for each measurement. The limiting of smoke spread was designed to cover the state of the smoke before moving to the upstream after passing over the soffit①. An anemometer to set the air velocity was installed for 12 points at a spot 2.0 (m) upstream the soffit①, and that to measure the velocity of the air passing through the cross section under the soffit① was installed for 10 points.

TABLE 1 Mesuring instruments

	Equipment Name	Measuring interval
Temperature	·K-type thermo couple ϕ 0.32 ·Dotting recorder HR2500 Yokogawa Electric	10 seconds
Air velocity	·Multi-point anemometer F6103 Shibaura Kogyo	5 minutes

2.4 Experimental method

TABLE 2 shows the conditions of the experiment. The height of origin of plume was changed to FL±0 (m) ~ FL + 1.5 (m) to adjust the smoke layer temperature. Since the air velocity under the soffit① does not form a uniform distribution, an airflow rate was calculated from the air velocity at 2.0 (m) upstream of the soffit① and the cross section of the passage.

TABLE 2 Experiment condition

Case name	Soffit① bottom height (m)	Soffit② bottom height (m)	Plume origin height (m)	Set wind velocity (m/s)	Actual wind velocity (m/s)
CASE1-1	FL+2.0	FL+1.5	FL±0	0.7	0.71
CASE1-2				0.6	0.61
CASE1-3				0.5	0.52
CASE1-4				0.4	0.39
CASE2-1	FL+2.0	FL+1.0	FL+1.0	0.7	0.68
CASE2-2				0.6	0.61
CASE2-3				0.5	0.51
CASE2-4				0.4	0.42
CASE3-1	FL+2.0	FL+1.5	FL+1.5	0.7	0.71
CASE3-2				0.6	0.61
CASE3-3				0.5	0.52
CASE3-4				0.4	0.42
CASE4-1	FL+2.3	FL+1.5	FL+1.5	0.7	0.66
CASE4-2				0.6	0.58
CASE4-3				0.5	0.48
CASE4-4				0.4	0.39
CASE5-1	FL+1.9	FL+1.5	FL+1.5	0.7	0.69
CASE5-2				0.6	0.57
CASE5-3				0.5	0.49
CASE5-4				0.4	0.39

The actual set air velocity is a mean air velocity obtained from the measured value at 2.0 (m) upstream of the soffit① converted into the air velocity passing through the cross section area under the soffit①. For origin of plume, an alcohol pan using methyl alcohol for fuel was used.

3. EXPERIMENTAL RESULT

3.1 Properties of temperature

FIGURE 4 shows the distribution of temperature rise before and after smoke prevention (CASE 3-1). From this, it can be found that two layers consisting of a smoke layer and an air layer are formed near the soffit①, and temperature distribution is generated inside the smoke layer vertically.The relationship between the thickness of smoke layer before smoke prevention and the temperature rise was studied. Since the smoke layer temperature near the soffit① is mostly stratified as shown in **FIGURE 4**, the temperature measured at each measuring point at 0.5 (m) downstream of the soffit① was defined to be the temperature of the smoke layer.

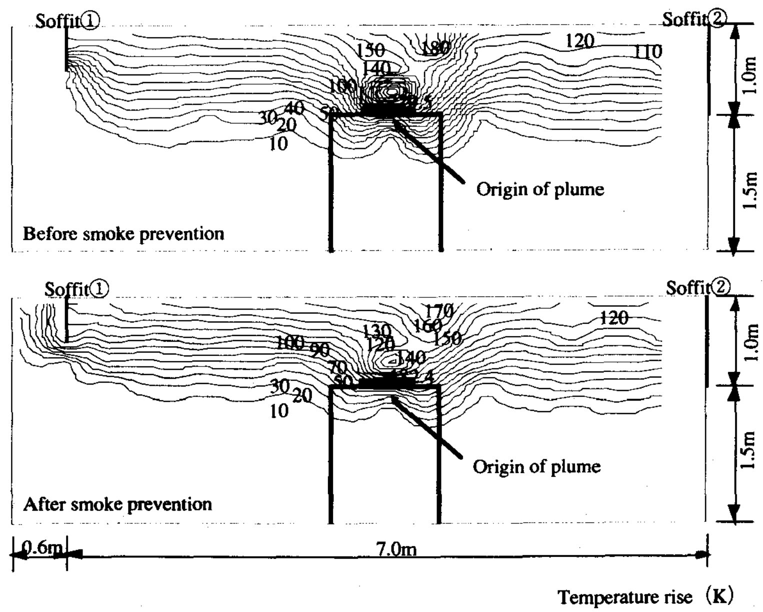


FIGURE 4 Distribution of temperature rise(CASE3-1)

FIGURE 5 shows the temperature rise before smoke prevention at 0.5 (m) downstream of the soffit①. From **FIGURE 5-a,** the temperature distribution inside the smoke layer is mostly uniform when the position of origin of plume is low, however, as the height of the position increases, the vertical temperature difference increases accordingly. When the experiment with the height of origin of plume of FL + 1.5 (m) and the supply air velocity of 0.7 (m/s) is compared with the experiment of **FIGURE 5-a ~ FIGURE 5-c**, the temperature rise is greater as the height of soffit① bottom lowers.

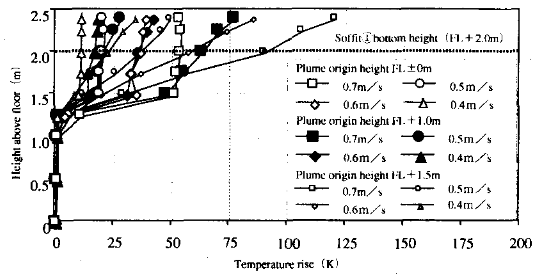


Figure 5-a Height of soffit① bottom FL+2.0m(CASE1-1~3-4)

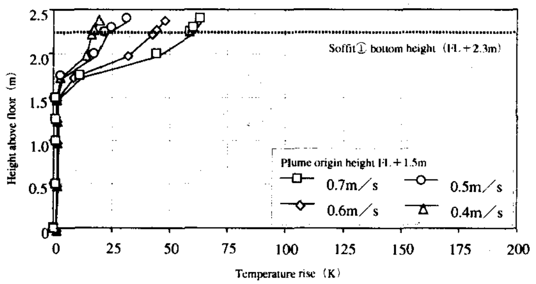


Figure 5-b Height of soffit① bottom FL+2.3m(CASE4-1~4-4)

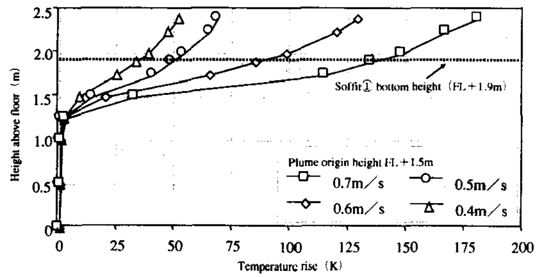


Figure 5-c Height of soffit① bottom FL+1.9m(CASE5-1~5-4)

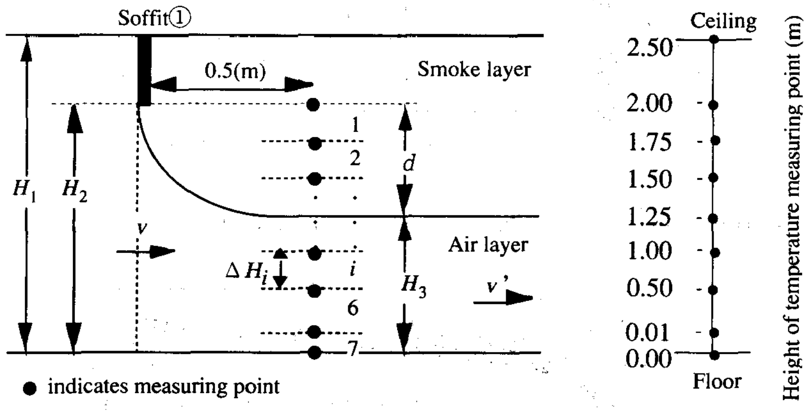
FIGURE 5 Distribution of temperature rise according to height

3.2 Distribution of buoyancy

The vertical distribution of the buoyancy $\triangle p$ before the smoke prevention was to be obtained. As shown in **FIGURE 6**, a part between temperature measuring points in vertical direction was defined to be one layer, and the spot of 0.5 (m) at the lower part of the soffit ① was divided in 7~8 layers horizontally. For the density of each layer ρ_i, the mean value of T_i' and T_i'', that represent the absolute temperature at the measuring points for the upper and lower parts of *i*-layer respectively was used. The buoyancy of each layer $\triangle p_i$ was calculated from Equation (2). **FIGURE 7** shows the vertical distribution of the buoyancy $\triangle p$ making the floor surface standard.

From this,it was found that the buoyancy of CASE5-1~CASE5-4 with the high temperature rise of the smoke layer is higher than that of other cases under the same air velocity of supplying air.

$$\rho_i = 353/\{(T_i' + T_i'')/2\} \quad (1)$$
$$\Delta p_i = \Delta H_i(\rho - \rho_i)\,g \quad (2)$$
$$\Delta p = \sum_{i=1}^{7\text{ or }8} \Delta p_i \quad (3)$$



Note)Thermo couple added at 0.5m downstream of the soffit ① for some experimental cases(1.9m or 2.3m)

FIGURE 6 Concept of calculating buoyancy

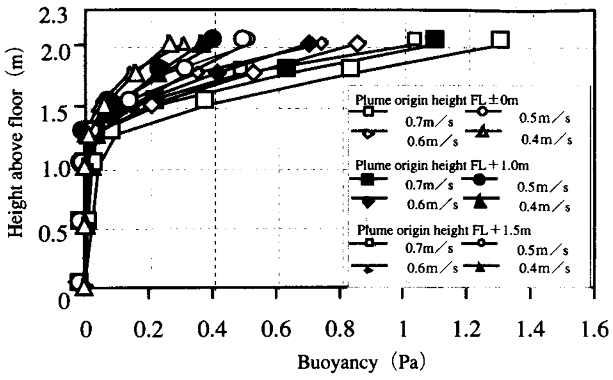


FIGURE 7-a Height of soffit① bottom FL+2.0m(CASE1-1～3-4)

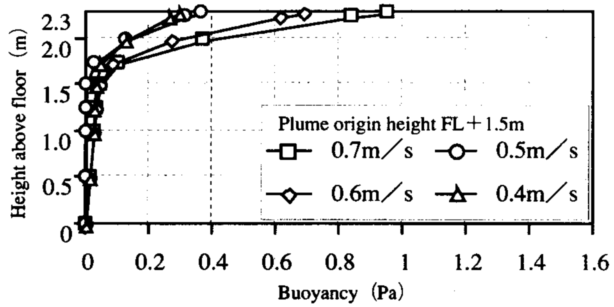


FIGURE 7-b Height of soffit① bottom FL+2.3m(CASE4-1～4-4)

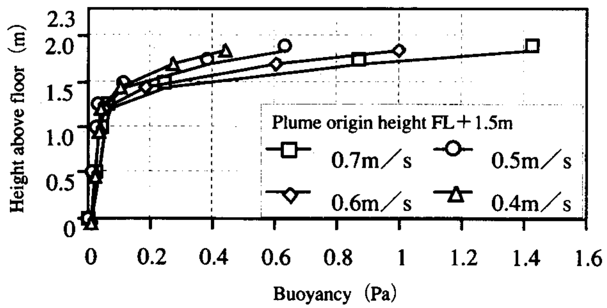


FIGURE 7-c Height of soffit① bottom FL+1.9m(CASE5-1～5-4)

FIGURE 7 Vertical distribution of buoyancy of smoke layer from base floor

4. THE CRITICAL AIR VELOCITY TO PREVENT THE SMOKE FLOW

In relation with the critical air velocity to prevent the smoke flow, the result obtained by this experiment and the conventional theoretical value by stratifying into 2 layers were compared[2)].

4.1 Relationship between the critical air velocity to prevent the smoke flow under the soffit ① and $(\Delta p/\rho)^{1/2}$

If the resistance on the wall surface caused by the airflow is disregarded, the buoyancy Δp of the smoke layer and the inertial force $(\rho v^2)/2$ of the supplying air will balance before the smoke prevention[Equation (4)]. Accordingly, the critical air velocity to prevent the smoke flow can be expressed as Equation (5) below. Calculating the buoyancy Δp from Equation (3), the relationship of the air velocity of supplying air v and inertial force $(\rho v^2)/2$ of the supplying air is as shown in **FIGURE 8**.

$$(\rho v^2)/2 \propto \Delta p \tag{4}$$
$$v = k_s (\Delta p/\rho)^{1/2} \tag{5}$$

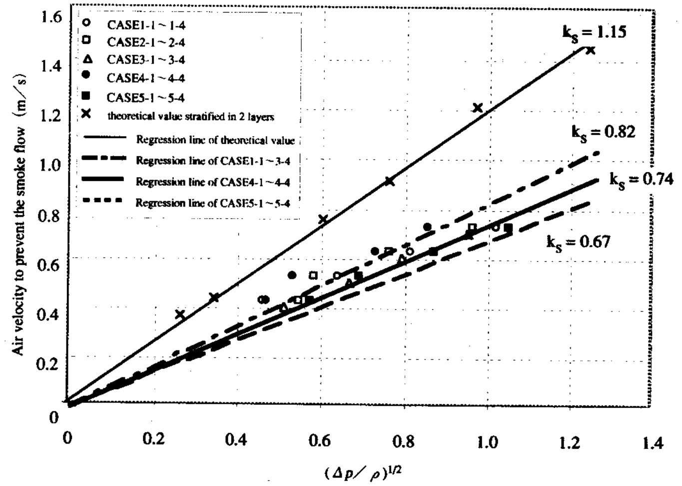


FIGURE 8 Relation between air velocity to prevent the smoke flow and $(\Delta p/\rho)^{1/2}$

The set air velocity under the state before the smoke layer is moving toward passing over the soffit ① was defined to be the critical air velocity.Here the equation by the theoretical value when conventionally stratifying into two layers was calculated under the following procedure.

By defining the differential pressure before and after the soffit ① at the smoke layer bottom when the smoke prevention is achieved to the buoyancy $\triangle p$ of the smoke layer, the thickness of the smoke layer to 0.5, 0.8 (m), the temperature of the smoke layer to 303, 323, and 373 (K) and the temperature of the supplying air to 298 (K), Q_1 and Q_2 were obtained from Equations (6) and (7). Then calculating the critical air velocity v from Equation (8), the relationship of v and $(\triangle p/\rho)^{1/2}$ was obtained.

$$Q_1 = 2/3 * \alpha A_1 (2\Delta p/\rho)^{1/2} \tag{6}$$
$$Q_2 = \alpha A_2 (2\Delta p/\rho)^{1/2} \tag{7}$$
$$v = (Q_1 + Q_2) / (A_1 + A_2) \tag{8}$$

From **FIGURE 8**, the following can be concluded.

(1)The critical air velocity to prevent the smoke flow spread v at the soffit ① bottom and $(\triangle p/\rho)^{1/2}$ are proportional.

(2)Regardless of the height of the soffit, the critical air velocity the smoke flow taking from the experiment shows a lower value than the value obtained by the conventional calculating method.

4.2 Relationship between the critical air velocity to prevent the smoke flow and $(\Delta \bar{\theta} d/T_s)^{1/2}$

To set a differential pressure at an opening, the critical air velocity to prevent the smoke flow can simply be obtained by using the thickness of smoke layer and temperature as an index. Assuming that the smoke layer temperature T_s to be uniform, it is calculated from Equation (9). Substituting Equation (9) for Equation (5) results in Equation (10),and where k_s' can be expressed by Equation (11).

$$\Delta p = (\rho g \Delta \bar{\theta} d) / T_s \tag{9}$$
$$v = k_s (\Delta \bar{\theta} d/T_s)^{1/2} \tag{10}$$
$$k_s' = k_s g^{1/2} \tag{11}$$

However, as the smoke layer thickness d is not completely clear in this experiment, the value of d was set by the procedure below. In the portion lower than soffit ① in **FIGURE 6**, the air velocity at the soffit bottom v and the buoyancy $\triangle p$ can be obtained as the equation below if the friction resistance of the inner wall of the passage is disregarded. From this, the wind velocity at the soffit bottom v can be expressed by Equation (13).

$$(\rho v^2)/2 + \Delta p = (\rho v'^2)/2 \tag{12}$$
$$v' = (v^2 + 2\Delta p/\rho)^{1/2} \tag{13}$$

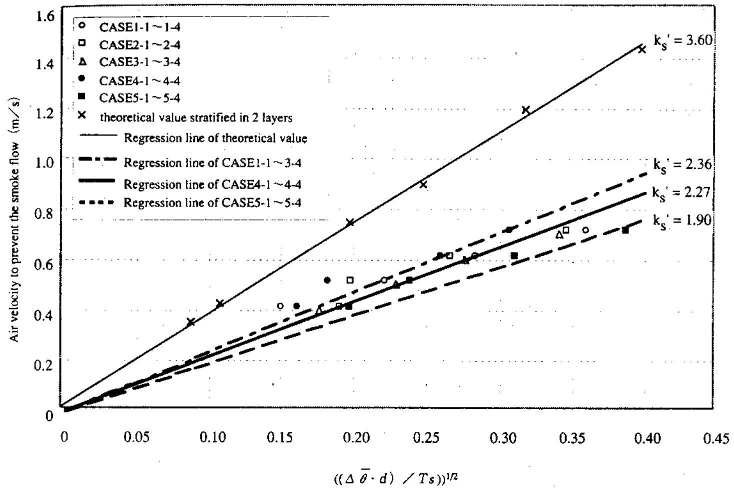


FIGURE 9 Relation between the air velocity to prevent the smoke flow and $((\Delta \bar{\theta} \cdot d)/T_s))^{1/2}$

Further, assuming that the supplying airflow rate at the upstream of the soffit ① Q and the air flow rate under the smoke layer Q' are equal, d was calculated by the following equation.

$$d = H_2 - H_3 = H_2 - Q/(v'W) \tag{14}$$

FIGURE 9 shows the relationship between the air velocity under the soffit ① v and $(\triangle \theta\ d/T_s)^{1/2}$. From this, the following can be concluded.

(1)Even when a soffit is installed, the critical air velocity under the soffit ① v and $(\triangle \bar{\theta}\ d/T_s)^{1/2}$ are in proportional relationship.

(2)Even when the smoke layer temperature is set to be uniform, the critical air velocity to prevent the smoke flow by the experiment is lower than the value obtained by the conventional calculating method regardless of the height of the soffit.

5. CONCLUSION

By considering the temperature distribution inside a smoke layer and clarifying the influence of a soffit or air movement under soffit, this study examined a possibility to set the air velocity of supplying air required to prevent the smoke flow adequately.

Although being limited to a horizontal passage, it was concluded that the air velocity under the soffit v and $(\triangle p/\rho)^{1/2}$, and v and $(\triangle \bar{\theta}/T_s)^{1/2}$ are in proportional relationship respectively.

6. REFERENCES

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SYMBOL

A_1 : Area from soffit ① bottom to smoke layer bottom under state where smoke spread is limited (m^2)
A_2 : Area from smoke layer bottom to floor under state where smoke spread is limited (m^2)
d : Height difference between soffit ① bottom and high temperature air layer bottom (m)
g : Gravitational acceleration (m/s^2)
H_1 : Ceiling height (m)
H_2 : Height of soffit ① bottom (m)
H_3 : Height of smoke layer bottom (m)
ΔH_i : Height of air layer i (m)
k_s : Coefficient
k_s' : $k*g^{1/2}$
Δp : Buoyancy of smoke layer before smoke prevention (Pa)
Δp_i : Buoyancy of air layer i (Pa)
Q : Flow rate of supplying air (m^3/s)
Q_1 : Airflow rate at passing A_1 section under state where smoke spread is limited (m^3/s)
Q_2 : Airflow rate at passing A_2 section under state where smoke spread is limited (m^3/s)
Q' : Airflow rate under smoke layer (m^3/s)
T : Absolute temperature of supplying air (K)
T_i' : Absolute temperature at upper measuring point of i layer (K)
T_i'' : Absolute temperature at lower measuring point of i layer (K)
T_S : Absolute temperature of uniform smoke layer (K)
v : Mean air velocity under soffit ① (Set air velocity) (m/s)
v' : Air velocity under smoke layer (m/s)
W : Width of passage (m)
$\Delta \bar{\theta}$: Difference between mean temperature of smoke layer and temperature of supplying air (K)
ρ : Density of supplying air (kg/m^3)
ρ_s : Density of smoke layer (kg/m^3)
ρ_i : Air density of i layer (kg/m^3)
α : Coefficient of opening (0.92)

POSTER ABSTRACTS