A Study of Smoke Behavior in a Compartment with Sprinkler System Activation -Theory and Validity on the Flow Rate of the Fire Plume during Sprinkler System Activation-

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1. OBJECTIVE AND BACKGROUND

In Japan, it is required by law to install a sprinkler system (hereafter, SP System) in accordance with the use of the building and its size. In general, the purpose of the SP System is to extinguish fires, and therefore most research reports are related to fire extinguishing. However, the influence of the SP system activation on the smoke layer has not yet been sufficiently assessed.

It is difficult to quantify the extinguishing time for SP systems, and the prediction of the behavior of the flames and the smoke, which is restricted by the SP systems, is still in the process of preliminary research. In order to be able to apply the influence of fire extinguishing equipment on the smoke behavior to the performance design, the effects of the sprinkling system need to be quantified. The successful evaluation and application of the fire suppression effects would allow for a more rational assessment of the fire performance, which is currently evaluated by assuming the emergence of an uncontrolled fire. Consequently, this would result in greater flexibility with respect to fire prevention planning

Therefore, this experimental study examined the influence on the smoke layer during sprinkling, in order to obtain information about smoke behavior during the SP system activation. In this paper, the changes occurring in the fire plume after sprinkling are reported.

2. PROPERTIES OF THE FIRE MODEL ASSUMED IN THIS STUDY

Figure 1 is a conceptual diagram of the smoke behavior within the fire compartment during the SP system activation. In *Figure 1*, the positions of the fire source and the water application are intentionally separated in order to illustrate the influence of the sprinkler on the smoke movement. Furthermore, for the sake of simplicity, the inside of the compartment is considered to be in a stationary state.

The fire plume caused by the combustion of the fire source rises up as entraining air from the lower layer, and penetrates into the smoke layer. Then, the flow rate m_p of the fire plume penetrating into the smoke layer is given as,

$$m_P = m_f + m_e \tag{1}$$

where the burning rate of the fire source is m_f, and the amount of the entrained air is m_e

Based on the mass conservation law between the upper and the lower layers, the following equations are given,

$$m_P - m_E - m_D = 0 \tag{2}$$

$$m_a + m_f - m_D = 0 \tag{3}$$

$$m_E = m_a - m_e \tag{4}$$

where the air entrained into the lower layer (downward flow rat) is m_E, the air released into the outside of the compartment from the openings (outflow rate) is m_D and the air entering the compartment (inflow rate) is m_a. Based on *Equations 3* and *4*, the following equations are given,

$$Y_L^{\infty} m_a + Y_L^f m_f - Y_L^S m_D = 0 \tag{5}$$

$$Y_L^a m_e = Y_L^{\infty} m_a + Y_L^S m_E \tag{6}$$

where Y_L^f is the generation rate of the chemical species L, which are generated by the combustion of the fuel, Y_L^S is the mass fraction of the chemical species L of the upper layer, Y_L^{∞} is the mass fraction of the chemical species L in the ambient air, and Y_L^a is the mass fraction of the chemical species L of the lower layer. (Refer to the end of this paper for the meaning of the above symbols subscripts).

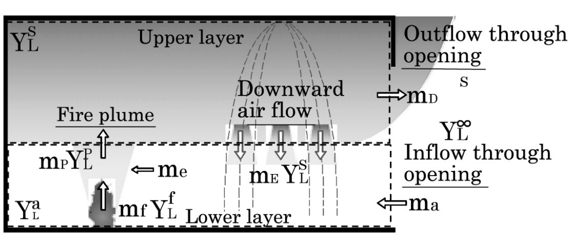

Figure 1 Conceptual diagram of the compartment

3. MASS FLOW RATE MEASUREMENT APPROACH BASED ON GAS ANALYSIS

The mass flow rate through an opening can be calculated from the temperature of the compartment and the flow rate of the openings [2, 3]. Also, as a method for measuring the fire plume flow rate, Zukoski *et al*. has proposed a method to analyze the gas concentration in the captured smoke by installing a hood directly above the fire source.[1] Yamaguchi et al. has proposed a method for measuring the flow rates and the jet plume of the opening by using a similar method.[4]

In this study, the in/out flow rates through the opening, fire plume flow rate and downward flow rate are measured in order to explore the smoke behavior in a compartment during the SP system activation. However, it is difficult to measure the flow rates of the fire plume and the downward airflow from the temperature of the compartment and the flow rate through the opening. Therefore, a flow rate measurement method based on gas analysis is employed in this study.

3.1 Equations for each flow rate

3.1.1 Flow rate of the fire plume m_p

The inflow rate through the opening m_p, the outflow rate through the opening m_a and the downward air flow rate m_e can be expressed as follows:

$$m_D = \left(\frac{Y_L^f - Y_L^\infty}{Y_L^S - Y_L^\infty} \right) m_f \tag{7}$$

$$m_a = \left(\frac{Y_L^f - Y_L^S}{Y_L^S - Y_L^\infty} \right) m_f \tag{8}$$

$$m_E = \left(\frac{Y_L^a - Y_L^\infty}{Y_L^S - Y_L^a} \right) \left(\frac{Y_L^f - Y_L^S}{Y_L^S - Y_L^\infty} \right) m_f \tag{9}$$

The fire plume flow rate is given by substituting *Equations 7* and *9* into *Equation 2*:

$$m_P = \left\{ \left(\frac{Y_L^f - Y_L^\infty}{Y_L^S - Y_L^\infty} \right) + \left(\frac{Y_L^a - Y_L^\infty}{Y_L^S - Y_L^a} \right) \left(\frac{Y_L^f - Y_L^S}{Y_L^S - Y_L^\infty} \right) \right\} m_f \tag{10}$$

From above, the fire plume flow rate m_p is given by measuring the generation rate of the chemical species L, Y_L^f, the chemical species concentration in the upper layer Y_L^S, the chemical species concentration in the lower layer Y_L^a, the chemical species concentration in the air, Y_L^∞ and the burning rate m_f.

3.2 Mass fraction

In order to obtain each flow rate by using the equations above, it is necessary to find out the mass fraction of chemical species. For that matter, the following section describes how the mass fraction can be derived from the volume fraction obtained by gas analysis.[4]

3.2.1 Volume fraction and mass fractions of the obtained gas

Assuming complete combustion for the fuel, O_2, CO_2, N_2 and H_2O are the only contents in the air. The following equations give the volume fraction of gas obtained at any arbitrarily chosen position and the relation between the volume fraction and the mass fraction, respectively:

$$X_{O_2} + X_{CO_2} + X_{N_2} + X_{H_2O} = 1 \tag{11}$$

$$Y_L = \frac{M_L X_L}{M_{O_2} X_{O_2} + M_{CO_2} X_{CO_2} + M_{N_2} X_{N_2} + M_{H_2O} X_{H_2O}} \tag{12}$$

The volume fraction X_{CO_2} of CO_2 is the target of the measurement.

3.2.2 Mass fraction of chemical species when methanol is used as fuel

The chemical equation for the complete combustion of methanol is as follows:

$$CH_3OH + \frac{3}{2} O_2 \rightarrow CO_2 + 2H_2O \tag{13}$$

When CO_2 is a tracer, the changes in the volume fractions for O_2, N_2 and H_2O can be deduced from the relation with the change in the volume fraction of CO_2.

$$X_{O_2} - X_{O_2}^{\infty} = -\frac{3}{2}\left(X_{CO_2} - X_{CO_2}^{\infty}\right) \tag{14}$$

Note that since water is not applied to the fire source directly in the intended model of this study, the water vapor generation induced by water droplets from the SP system is ignored.

According to *Equation 13*, nitrogen does not contribute to the chemical reaction. Therefore, assuming that it does not change, it can be expressed as follows:

$$X_{N_2} = 1 - X_{O_2}^{\infty} + X_{H_2O}^{\infty} - \frac{3}{2} X_{CO_2} + \frac{1}{2} X_{CO_2}^{\infty} \tag{15}$$

The mass fraction Y_{co_2} of CO_2 in the obtained gas can be given by substituting each molecular mass as follows:

$$Y_{CO_2} = \frac{22 X_{CO_2}}{2X_{O_2}^{\infty} - 5X_{CO_2} + 13X_{CO_2}^{\infty} + 23X_{H_2O}^{\infty} + 14} \tag{16}$$

Also, the mass fraction $Y_{co_2}^{\infty}$ of CO_2 in fresh air is given by substituting the mass fraction $X_{co_2}^{\infty}$ of CO_2 in fresh air into *Equation 16*:

$$Y_{CO_2}^{\infty} = \frac{11 X_{CO_2}^{\infty}}{7 + X_{O_2}^{\infty} + 4X_{CO_2}^{\infty} + 23X_{H_2O}^{\infty}} \tag{17}$$

4. VALIDATION OF THE GAS ANALYSIS METHOD

In order to verify the validity of the measurement method of the mass flow rate that is based on the gas analysis, a comparison between the flow rates through the openings based on flow distribution and gas analysis was conducted. Considering the gas concentration and the flow velocity that are necessary for this verification, a post-ignition average rate of 540 to 600 seconds was used, since the gas in the compartment is in a quasi-stationary state during that period.

4.1 Calculation based on the flow distribution through the openings

Figure 2 shows the comparison between the flow rates through the openings based on gas analysis and wind velocity. Both flow rates through the opening are very consistent, which indicates that the measurement method based on gas analysis is as accurate as the method based on flow velocity.

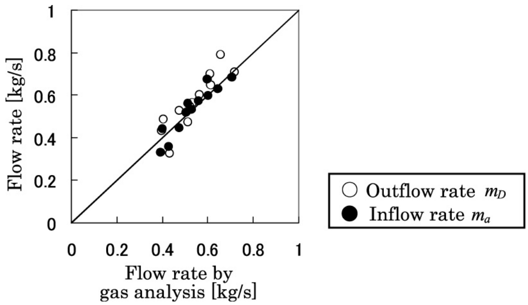

Figure 2 Flow rate at the openings

4.2 Estimation method for the mass loss rate of the fuel based on gas analysis

Using the mass conservation law, the burning rate m_f is given as

$$m_f = \frac{33}{42}\Delta m_{CO2} \tag{18}$$

$$m_f = \frac{8}{3} m_D \left(Y^S_{CO_2} - Y^a_{CO_2} \right) \tag{19}$$

where the molecular mass of the methanol is 32, the molecular mass of the CO_2 generated by combustion is 44, and the generation rate is Δm_{co_2}

Figure 3 shows a comparison between the burning rate calculated from the gas concentration and the mass loss rate obtained from the load cell. The burning rate obtained from the gas concentration and the mass loss rate obtained from the load cell are very consistent, which indicates that the burning rate measurement method of based on gas analysis is as accurate as the method based on the load cell.

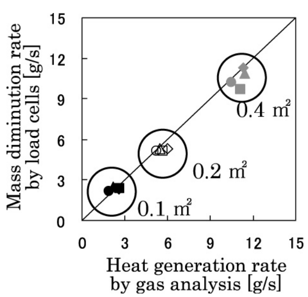

Figure 3 Mass loss rate and burning rate

5. CONCLUSION

- It is possible to measure the fire plume flow rate based on the gas concentration of CO_2 during sprinkling by using the traditional methods.
- The measurement results and the sprinkler's influence on the fire plume will be reported in the next experiment.

SYMBOLS

p : concentration [kg/m^3]
T : temperature [K]
g : gravitational acceleration [m/s^2]
Q : heat release rate [kW]
Q_c : heat transfer by convection
m_p : fire plume rate [kg/s]
m_f : burning rate [kg/s]
Y : concentration of chemical species
X_L : volume fraction [m^3/m^3]
Y_L : mass fraction [kg/kg]

SUBSCRIPT

S : smoke layer
a : lower layer
∞ : ambient air
e : entrained air
D : jet flow
E : downward airflow

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