

Study of Smoke Behavior in a Compartment with Sprinkler System Activation

- Measurement and Analysis of Fire Plumes -

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1. OBJECTIVE OF THE EXPERIMENT

Sprinkler systems (hereinafter, SP systems) are one of the important fire safety measures with respect to building fire safety. However, with the exception of the relaxation of the fire compartment, the current architectural design does not take into significant consideration the effects of SP systems. If the effects of SP systems could be applied in architectural design, it would allow greater flexibility in the design and would improve the current fire safety measures.

Activating an SP system induces air flow that brings smoke accumulated in the upper ceiling area down to the lower area (hereinafter, downward air flow).[1] On the other hand, the downward air flow changes the air flow in the entire compartment, which may influence the entraining behavior of the fire plume.

Current research commonly makes use of Zukoski's and Heskestad's models in order to estimate the flow rate of the fire plume. However, the compartmental setting of these models is controlled and the influence of the ambient air flow that is changed by the water discharge is not taken into account. Therefore, this study investigates the impact of the water discharge on the fire plume by calculating the fire plume from the models of Zukoski and Heskestad and comparing it with the fire plume as obtained from an experiment involving an actual-size fire compartment.

2. INTENDED MODEL OF THIS STUDY

Figure 1 presents an outline of this experiment based on the concept of the two-layer zone model. For the sake of simplicity, no water was sprinkled on the fire source, and the compartment was in a stationary state.

The fire plume flow rate m_p can be calculated from the following equation [2],

$$m_p = \left(\frac{Y_L^f - Y_L^a}{Y_L^h - Y_L^a} \right) m_f \quad (1)$$

where the gas concentration inside of the hood and lower layer is Y_L^h and Y_L^a , the generation rate of the chemical species L is (Y_L^f) , and the burning rate is (m) . It should

be noted that a hood is placed directly above the fire source in order to identify the entraining height of the fire plume.

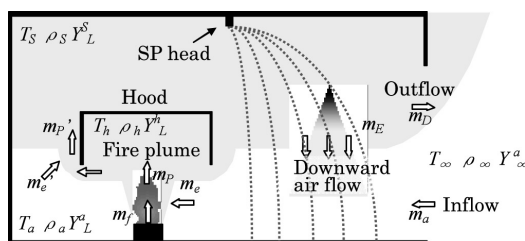


Figure 1 Conceptual diagram of the experiment

3. EXPERIMENTAL SUMMARY

3.1 Experimental compartment

Figure 2 is an image of the compartment used for this experiment. The inside dimensions of this compartment are as follows: Width 6500 mm \times Depth 6500 mm \times Height 2700 mm.

3.2 Measurement parameters

Thermocouples were placed in several positions. The vertical temperature distribution of the compartment was measured in the left and right corners (Trees A and C) as well as in the center of the compartment (Tree B) by installing thermocouples at 300 mm intervals in vertical direction. Thermocouples were also placed inside the hood at 100 mm intervals in vertical direction (Tree H).

The CO_2 concentration of the compartment was measured in the left and right corners, whereby the sensors were placed at 0 mm and 2000 mm from the floor. It was also measured at the opening at a height of 200 mm from the floor, as well as inside the hood.

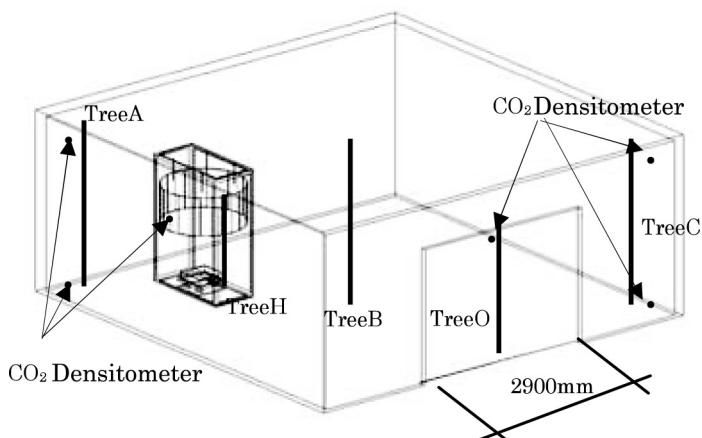


Figure 2 Experimental compartment

3.3 Experimental conditions

Table 1 shows the conditions of the experiment. Thirty-four different experiments were carried out in the compartment by changing the size (area) of the fire source, the amount of water and the height of the hood.

Table 1 Experimental conditions

Area of the fire source (m ²)	Hood height (mm)	Amount of water (ℓ/mm)
0.1, 0.2, 0.4	900, 1050, 1200, N/A	0, 20, 40, 60

3.3.1 Fire source conditions

The fuel of the fire source is methanol. The area of the fire source was changed from 0.1 m² to 0.2 m² and 0.4 m².

3.3.2 Water discharge conditions

The quality of the water droplets was kept the same in this experiment; however, the amount of water was changed from 0 ℓ/mm to 20 ℓ/mm, 40 ℓ/mm and 60 ℓ/mm by using a water intake box which is capable of limiting the size of the watered area.

3.3.3 Hood height

The height of the hood's bottom end, as measured from the floor of the compartment, was changed from 900 mm to 1050 mm and 1200 mm, and the case without a hood was also investigated.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The most frequent result obtained in this experiment was that the fire plumes penetrated into the smoke layer in the areas where flame was continuous. Therefore, those areas will be the main focus of this report.

4.1 Experimental results

Figure 3 shows a comparison of the fire plume flow rate m_p and the distance Z between the fire source and the bottom of the smoke layer inside the hood, when the amount of water was set to 60 ℓ/mm for each fire source area. It should be noted that the height of the smoke layer was calculated by applying the N% method [3] to the smoke layer's temperature distribution (Tree H) inside the hood.

As a general observation, the fire plume flow rate tends to increase as the distance from the fire source becomes larger. Figure 3 also shows a similar tendency.

Figure 4 is a comparison between the fire plume flow rate m_p in the hood at a height of 1200 mm, and the width D of the fire source.

As shown in Figure 4, the fire plume flow rate tends to increase as the width of the fire

source becomes larger. Also, the amount of water did not exert any significant influence on the fire plume flow rate.

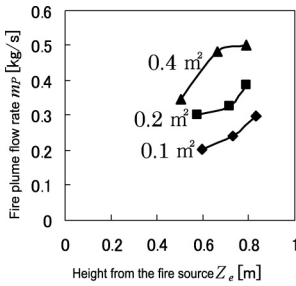


Figure 3 Comparison with respect to the fire source area

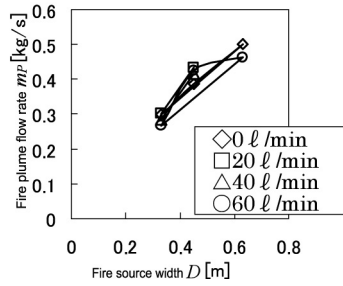


Figure 4 Comparison with respect to the amount of water

4.2 Comparison with the traditional equations

(1) Zukoski Model

Zukoski suggested a prediction equation with respect to the fire plume flow rate in the continuous flame area as follows,

$$m_p = 0.447 \rho_a D Z_e^{3/4} \quad (2)$$

Zukoski also estimated the average flame height on an experimental basis as follows,

$$Z_{fl} = 3.3 D Q_D^{*2/3} \quad (Q_D^* < 1) \quad (3)$$

Here, Q_D^* is a dimensionless generation rate which can be defined as follows,

$$Q_D^* = \frac{Q_f}{c_p \rho_\infty T_\infty g^{1/2} D^{5/2}} \quad (4)$$

where Q_f is the generation rate and D is the diameter of the fire source.

(2) Heskestad Model

Heskestad suggested prediction equations with respect to the fire plume flow rate as follows,

$$m_p = 0.0054 Q_c Z_e / \left(0.166 Q_c^{2/5} + Z_0' \right) \quad Z_e \leq Z_1 \quad (5)$$

$$m_p = 0.071 Q_c^{1/3} \left(Z_e - Z_0' \right)^{5/3} \left[1 + 0.026 Q_c^{2/3} \left(Z_e - Z_0' \right)^{-5/3} \right] \quad Z_e > Z_1 \quad (5)'$$

$$Z_1 = Z_0' + 0.166 Q_c^{2/5} \quad Z_0' = -1.02 D + 0.083 Q_f^{2/5}$$

Here, the convective component was calculated as 2/3 of the total.

$$Q_c = 2/3 \times Q_f \quad (6)$$

The average flame height Z_{fl} can be given as follows,

$$Z_{fl} = 0.23 Q^{2/5} - 1.02 D \quad (7)$$

(3) Comparison with the experimental values

Figure 5 is a comparison between the fire plume flow rate as obtained from this experiment and the predictive values calculated from the Zukoski and Heskestad models.

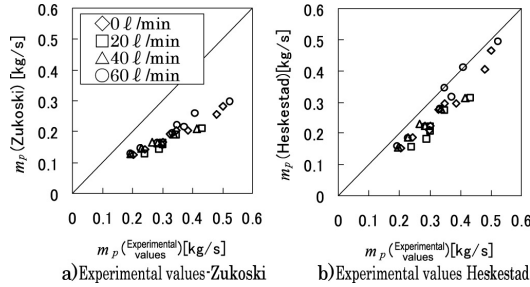


Figure 5 Comparison between the values of the fire plume

According to Figure 5 a), the fire plume flow rate obtained from this experiment is 1.6 to 2.2 times greater than that of the Zukoski model.

Furthermore, according to Figure 5 b), the fire plume flow rate obtained from this experiment is 1.1 to 1.4 times greater than that of the Heskestad model.

Figure 6 shows a comparison between the smoke height and the fire plume flow rate. The x-axis indicates the values of the height Z_e from the fire source divided by the average height Z_{fl} and the y-axis indicates the values of the burning rate m_f divided by the fire plume rate m_p . For the Zukoski model, the values used in this comparison are the fire plume flow rate which can be calculated from the prediction Equation 2 and the values based on the average flame height which can be calculated from Equation 3. For the Heskestad model, the values used in this comparison are the fire plume flow rate which can be calculated from the prediction Equation 5 and the values based on the average flame height which can be calculated from Equation 7.

Based on Figure 6, there is a proportional relation between m_p/m_f and Z_e/Z_{fl} , which leads to the following relation,

$$\frac{m_p}{m_f} = \beta \frac{Z_e}{Z_{fl}} \quad (8)$$

The average value of β is 110 in the experimental results, as compared to 62 and 74 in the Zukoski and Heskestad models, respectively. The Heskestad and Zukoski models are designed with the assumption that the air inside of the compartment is controlled, but it is actually possible to assume that the fire plume flow rate is influenced by the disturbed air flow inside the compartment caused by wind blowing from the openings and water discharged from the sprinklers. This proves that the conventional fire plume models do not take into account sufficient information about the smoke behavior inside the compartment.

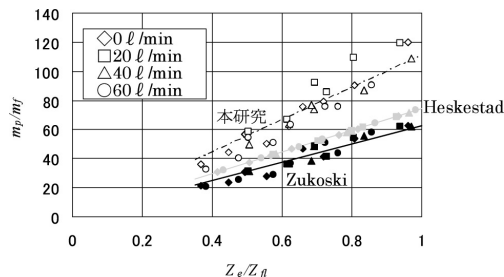


Figure 6 Fire plume flow rate and smoke layer height

5. CONCLUSION

- The fire plume flow rate of the continuous flame area was not influenced by the water discharged from the sprinkler.
- Inside the compartment, the fire plume flow rate of the continuous flame area is 1.6 to 2.2 times that of the Zukoski model and 1.1 to 1.4 times that of the Heskestad model.
- The influence of discharging water on the fire plume flow rate will be investigated in future experiments.

SYMBOLS

p : concentration [kg/m^3]

T : temperature [K]

g : gravitational acceleration [m/s^2]

m_p : fire plume rate [kg/s]

Q : heat release rate [kW]

Q_c : heat transfer by convection

m_f : burning rate [kg/s]

Y : concentration of chemical species

D : representative width of the fire source [m]

Z_e : height from the fire source [m]

Subscript

h : inside hood

s : smoke layer

a : lower layer

∞ : ambient air

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