

# Predictive Method for Properties of Flame Ejected from an Opening Incorporating Excess Fuel

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## ABSTRACT

The purpose of this study is to investigate the properties of external flames ejected from an opening by conducting a small-scale fire test and to develop a method for predicting external flame properties taking into consideration the combustion of excess fuel gas in the external flame. Findings from this study can be summarized as follows: ①The critical heat release rate of external flame and the heat convected out by the airflow from an opening under conditions where external flaming occurs tend to increase with  $AH^{1/2}$ . ②Dimensionless values obtained by dividing the height of the average flame tip measured along the central axis of external flame by the representative length of the opening are approximately proportional to the two-third power of the dimensionless heat release rate. ③ A correction value  $\Delta z$  calculated from the dimensionless heat release rate, which is calculated from the total rate of heat release of flame ejected from an opening, can be used to predict the temperature of external flame at its central axis, taking into consideration the heat release rate due to the combustion of excess fuel gas.

Key words: external flame , excess fuel, heat release rate , dimensionless heat release rate , virtual heat source

## 1 Introduction

### 1.1 Purpose

When a fire that broke out in a building spreads, there are cases where flames are ejected from windows. Since flames spouting from windows can be a major cause of fire spread to adjoining floor or neighboring buildings and the resultant aggravation of fire damage, knowing the properties of such flames is of great importance to building fire safety. The subject of flames projecting from windows has been studied by other investigators , and various methods for evaluating fire spread to upper floors or neighboring buildings have been proposed. <sup>(for example, 1)-4)</sup> Among these methods, the method of predicting fire spread to upper floors in a building proposed by Yokoi as a result of his pioneering work is still in general use for building design and other purposes.

The quantity of combustible materials brought into buildings has increased in recent years. This has increased the possibility of fires involving longer flames projecting from windows, and it has been pointed out that the Yokoi method could underestimate the risk of fire spread by the external flame.<sup>9</sup> Yokoi's study showed that temperatures of flame projecting from a window at the central axis of the flame can be predicted if the window conditions and the fire room temperature near the window are given. The present study, however, is based on assumption that fire plumes over a fire source form over a point heat source. Consequently, a theoretical contradiction may arise in cases where a large quantity of excess fuel gas is discharged from the fire compartment because of, for example, a lack of oxygen supply in the compartment.

Several studies have shown that properties such as the height and temperature distribution of turbulent diffusion flames over a point heat source are related with factors such as the diameter and heat release rate of the fire source. Many methods based on the virtual source theory have been proposed as more or less standard methods for predicting flame properties.<sup>6,10</sup> etc. In the case of flame projecting from a window, if it is assumed that its properties are dependent on the cross-sectional shape of the external flame and the amount of heat release in the flame at the window, it may be possible to use the virtual source theory to predict the properties of the external flame.

The purpose of this study is to investigate the properties of external flames by conducting an experiment using a small-scale compartment model and to develop a method for predicting external flame properties that takes into consideration the combustion of excess fuel gas in the external flame.

### 1.2 Heat release rate of flame projecting from opening

For the calculation process of temperature of external flame at its central axis, Yokoi regarded the quantity of heat  $Q_Y$  in the external flame as the enthalpy carried away by hot air outflow through the window (it is assumed here, however, that only the upper half of the window opening is thought of as the cross section of flame) and calculated  $Q_Y$  using the following equation:

$$Q_Y = c_p \Delta T_f \alpha B \rho \int_{H/2}^H v(h) dh \quad (1)$$

Therefore, the quantity of heat  $Q_Y$  calculated from Eq. (1) is dependent on the compartment fire temperature and the window conditions. Since the compartment fire temperature is dependent on the compartment conditions and the window conditions, it follows that the quantity of heat  $Q_Y$  depends on the window and compartment conditions. Namely, because Yokoi's method does not taking into account the combustion of excess fuel gas in the external flame, which is thought to vary depending on the fuel conditions, the method of estimating the quantity of heat of the external flame becomes inadequate in cases where a large amount of excess fuel gas is discharged.

For the purposes of this study, to build a model that takes into consideration the combustion of excess fuel gas in the external flame, the total heat release rate  $Q_{et}$  of the external flame is defined as the sum of the heat  $Q_c$  convected out by the airflow and the heat release rate  $Q_f$  due to the combustion of the excess fuel gas contained in the external flame. The heat convected out by the airflow,  $Q_e$ , can be calculated from the rate of air flow through the window and the compartment fire temperature, using the following equation:

$$Q_e = c_p R_{f0} \Delta T \approx 0.5 c_p A \sqrt{H} \Delta T \quad (2)$$

The rate of heat  $Q_f$  due to the combustion of the excess fuel gas outside the fire compartment is assumed to be obtainable by subtracting the heat release rate due to combustion of the fuel gas in the compartment, that is the critical heat release rate  $Q_{crit}$  to generate the external flame, from the heat

release rate  $Q_c$  of combustible gas generated in the compartment, and is calculated from the equation

$$Q_f = Q_c - Q_{crit} \quad (3)$$

Where  $Q_{crit}$  relates to conditions of opening, compartment wall and fuel. Hence, the total heat release rate  $Q_{et}$  of external flame can be defined as follows:<sup>11</sup>

$$Q_{ef} = Q_e + Q_f = c_p R_{f0} \Delta T + Q_c - Q_{crit} \quad (4)$$

Let  $m_f$  be the amount of excess fuel gas;  $m_c$ , the amount of fuel gas generated in the fire compartment; and  $R_{op}$ , the rate of air inflow into the compartment. Then, the relationship of Eq. (3) can be expressed as

$$m_f = m_c - v \frac{R_{of}}{\gamma} \quad (5)$$

where  $\gamma$  is the stoichiometric air/fuel ratio; and  $v$ , the efficiency with which the air that has flowed into the fire room contributes to the combustion of fuel gas in the compartment (excess air ratio). It has been reported<sup>12</sup> that the value of  $v$  varies with the position of fire source in the fire compartment and the condition of the opening. If it is assumed that the excess fuel gas completely burns out outside the fire compartment,  $Q_f$  can be expressed, using the combustion heat  $\Delta H$  of fuel gas assuming complete combustion, as

$$Q_f = \Delta H (m_c - v \frac{R_{of}}{\gamma}) \quad (6)$$

Therefore, the critical heat release rate  $Q_{crit}$  for external flaming can be expressed as

$$Q_{crit} = \Delta H v \frac{R_{of}}{\gamma} \quad (7)$$

Several investigators have reported their findings about  $Q_{crit}$ . Hagglund and others conducted the small scale fire tests using wooden cribs as fuel and proposed a method for judging the generation limit of external flame by evaluating the burning rate. From their experiment results, they concluded that there is a lower limit to the burning rate at which external flaming occurs and that burning rate is determined solely by the ventilation factor.<sup>13</sup> Jannsson, Onnermark and others conducted the fire tests using a full-scale room as well as the small scale fire tests carried out by Hagglund and others, determined the critical burning rate from the ventilation factor.<sup>14</sup> Hasemi carried out the small scale fire tests using propane gas as a source of fire to investigate the mechanism of external flaming from a window in a fully developed fire.<sup>15</sup> As a result, he reported that the critical heat release rate for external flaming is affected not only by the ventilation factor but also by compartment size. Further, Hasemi also compared their experiment results with the results of the full-scale fire tests using a gas burner conducted by Oleszkiewicz and reported that the critical heat release rate for external flaming is strongly correlated with the fire temperature factor  $A_T/AH^{1/2}$ , which is an indicator of thermal characteristics of the compartment.

## 2 Experimental method

### 2.1 Experimental apparatus

The apparatus shown in Fig. 1 was used in the experiment. The compartment model was a 0.6-meter cube made of 0.02-meter-thick perlite boards and 0.01-meter-thick ceramic fiberboard lining. To measure vertical temperature distribution in the compartment, a vertical array of 12 thermocouples

(K type, 0.65 mm in diameter, located at a point 0.025 m from the ceiling of the compartment and at 0.05 m spacings below it) was installed at two locations: the near right corner and the far left corner from the opening. Thermocouples were also installed at a point 0.01 m from the lower edge of the opening and at 0.02 m spacings above it to measure vertical temperature distribution of air flowing out of and into the compartment through the opening.

Temperatures of the flame projecting from the opening were measured with thermocouples installed as shown in Fig. 1a). A row of 11 thermocouples was installed horizontally along the opening at 0.05 m spacings. Four parallel rows, spaced 0.025 m apart, of 11 thermocouples were installed along the first row; four more rows were installed at 0.05 spacings; and another row at a distance of 0.1 m. The plane on which these thermocouples were located was defined as the temperature measurement plane, and it was moved up and down as shown in Fig. 1b) to measure the vertical temperature distribution of the flame projecting from the opening.

As the source of fire, a 0.1 m × 0.1 m diffusion type gas burner was installed at the center of the compartment model, and the burner was fueled by methane gas.

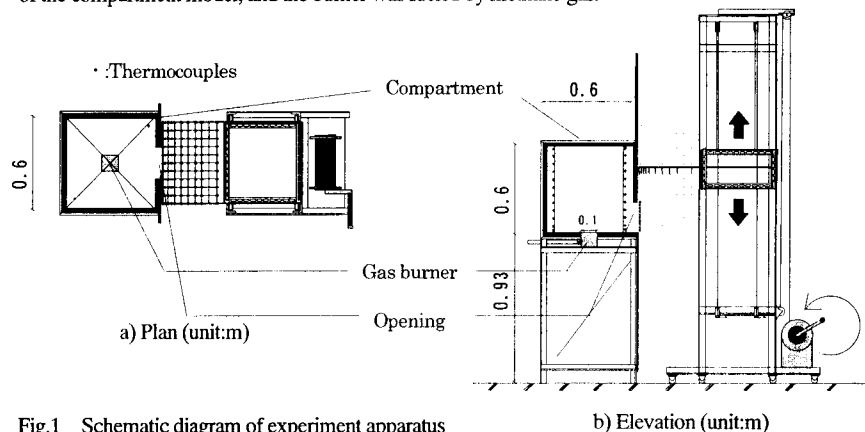


Fig.1 Schematic diagram of experiment apparatus

### 2.2 Measurements in the experiment

Measurements in the experiment were made by following the procedure described below.

- (1) After starting to supply methane gas to the gas burner, ignite the gas burner and heat the compartment until temperature in the compartment becomes more or less constant.
- (2) After making sure that temperature in the compartment is more or less constant, measure the temperature of the flame projecting from the opening. One-fourth of the height of the opening was defined as reference height  $H$ , and measurements were taken at 13 levels at  $H$  spacings from the lower edge of the opening and at two 2 levels at  $2H$  spacings above the 13 levels. Temperature was measured with the thermocouples at 2-second intervals, and measurements were recorded continuously for 30 seconds.
- (3) On completion of the temperature measurement, the thickness of the flame projecting from the opening and the height of flame were recorded with a video camera.

The shape of the external flame and the height of flame were calculated from the video images as 20-second averages. As for the temperature of the external flame, 30-second averages obtained from individual measurement points were taken as representative values.

### 2.3 Experiment conditions

In the experiment, the width and height of the opening and the discharge rate of methane gas supplied to the gas burner were varied. Table 1 shows the relationships between the opening conditions and the heat release rate of the fire source calculated by assuming complete combustion of the methane gas supply rate under the conditions used in the experiment. As shown in Table 1, three heat release rates were used for each type of an opening.

Table 1 Experiment conditions

Opening dimension		Heat release rate		
Width B(m)	Height H(m)	(kW)		
0.2	0.1	10.1	11.1	12
0.2	0.15	10.2	11.9	13.5
0.2	0.2	14.3	16.9	20.9
0.15	0.2	11.7	13.7	15.6
0.1	0.2	9.1	10.4	12.1
0.05	0.2	7.8	8.1	9.1

## 3 Results and discussion

### 3.1 Time-curve of temperature and height of external flame

Figure 2 shows changes over time in average temperature in the compartment at different rates of heat release from the gas burner, in temperature near the external wall surface at a level 15 cm above the upper edge of the opening, and in the height of average flame tip of the external flame. In Fig. 2, the origin of the time axis is the time at which the gas burner is ignited.

Figure 2a) shows changes over time in average temperature in the fire compartment, i.e., average value of temperature measured by whole thermocouples constituted in the compartment. As shown, average temperatures in the fire compartment began to rise rapidly immediately after the gas burner was ignited, and about 30 minutes later temperatures began to approach more or less constant values, that is, a steady state. Comparison of these more or less steady temperatures reveals that the temperatures at the lowest heat release rate (14.3 kW) are about 70 K lower than those at the other two heat release rates (16.9 kW and 20.9 kW), while the average temperatures in the fire compartment at these two heat release rates are roughly the same.

Figure 2b) shows changes over time in temperature near the wall (the distance from the wall to the thermocouple junction is about 5mm) at a vertical distance of 15 cm from the upper edge of the opening, at different heat release rates. As in the case of the temperatures in the fire compartment, the temperatures of air near the wall began to rise immediately after the gas burner was ignited, and constant values began to appear about 30 minutes after the ignition of the gas burner. Comparison of the changes in temperature near the wall reveals that the higher the heat release rate, the higher the temperature tends to be. Therefore, although the temperatures in the fire compartment were roughly the same at the heat release rates of 16.9 kW and 20.9 kW, the temperatures near the wall were higher at 20.9 kW.

Figure 2c) shows the height of the average flame tip measured along the central axis of external flame. The results shown in this figure indicate that the higher the heat release rate, the greater the length of the average flame tip tends to be. Thus, it can be seen from Fig. 2 that there are cases where temperatures above the opening and the height of average flame tip vary even if temperatures in the fire compartment are roughly the same. The reason for this result is thought to be that, as explained earlier in this paper, although the heat release rate due to the combustion of excess fuel gas  $Q_c$  remains unchanged if the temperature in the fire compartment and the opening conditions remain equal, the heat release rate due to the combustion of excess fuel gas,  $Q_p$ , varies. Namely, as shown in Table 2, in case the opening is same dimension, the thickness of external flame at an opening is roughly the same regardless of the heat release rate.

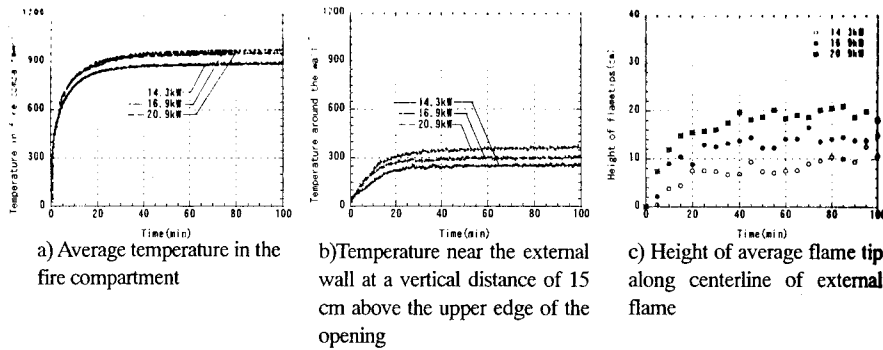


Fig. 2 Time-curve of temperature and height of external flame(Opening dimension:0.2m(B)×0.2m(H))

### 3.2 Heat release rate related to properties of external flame

This section deals with the results of calculation of the heat release rate related to properties of external flames under different experiment conditions. For the purposes of the experiment, the rate of heat release due to the combustion of excess fuel gas,  $Q_p$ , is defined as the value,  $Q_c$ , shown in Table 1 minus the critical heat release rate  $Q_{crit}$  for external flaming, which is the rate of heat release at which continuous flame projection from the opening begins. The total heat release rate in external flame,  $Q_{ef}$  is defined as the sum of  $Q_c$  and  $Q_e$ . Figure 3 shows the calculation results for  $Q_c$ ,  $Q_{crit}$ ,  $Q_e$ , and  $Q_{ef}$ . According to these results,  $Q_{crit}$  and  $Q_e$  under the conditions ejected external flame tend to increase with the ventilation factor  $AH^{1/2}$ .

Figure 4 shows the results for the critical heat release rate  $Q_{crit}$  shown in Fig. 3. The vertical axis indicates  $Q_{crit}/AH^{1/2}$ ; and the horizontal axis,  $A_T/AH^{1/2}$ . In addition to the experiment conditions of Table 1, Fig. 4 also shows measurement results for an opening height of 0.1 m and opening widths of 0.075, 0.1, and 0.125 m, which were determined using the experiment model prepared for the above experiment, and some of the previously reported study results.<sup>12), 15)</sup> It can be seen from these results that the experiment results for the critical heat release rate  $Q_{crit}$  plot approximately linearly. An

Table 2 Thickness of external flame

Opening dimension Width B(m)	Height H(m)	Thickness of external flame(m)
0.2	0.1	0.039
0.2	0.15	0.063
0.2	0.2	0.07
0.15	0.2	0.078
0.1	0.2	0.084
0.05	0.2	0.11

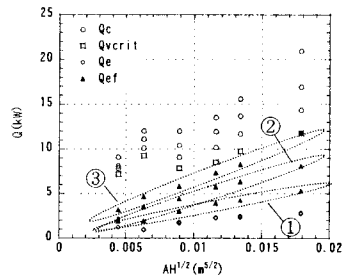


Fig.3 Heat release rate as a function of ventilation factor  $AH^{1/2}$

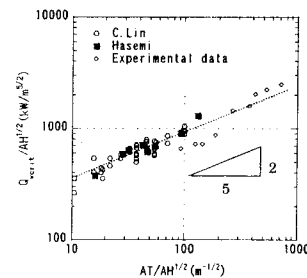


Fig.4 Relationship between  $Q_{crit}$  and  $A_T/AH^{1/2}$

equation for regression to the experiment results has been derived:

$$\frac{Q_{crit}}{A\sqrt{H}} = 150 \left( \frac{A_T}{A\sqrt{H}} \right)^{2/5} \quad (8)$$

### 3.3 Height of external flame

Thomas, Yokoi and others investigated the height of flames projecting from an opening over which there is no wall and derived the following relation:<sup>16), 17)</sup>

$$\Theta \propto \left( \frac{n^{1/3}z}{r_0} \right)^{-1} \quad (9)$$

where  $n$  is the aspect ratio ( $n=2B/H$ ,  $B$ : width of opening,  $H$ : height of opening) of the opening and  $r_0$  is the equivalent opening radius ( $r_0=(BH/2\pi)^{0.5}$ ). For  $z$ , Thomas adopted the vertical height of external flame, and Yokoi opted for the length of external flame along its central axis. If there is a wall over the opening, the  $n$  can be neglected<sup>17)</sup>, so that Eq. (9) becomes

$$\Theta \propto \left( \frac{z}{r_0} \right)^{-1} \quad (10)$$

From dimensionless temperature  $\Theta$ , the relation Eq.(11) is derived.

$$\Theta = \frac{\Delta T r_0^{5/3}}{T_\infty Q^{2/3}} \propto \frac{\Delta T r_0^{5/3}}{\left( \frac{Q}{\rho} \right)^{2/3}} = \Delta T \left( \frac{\rho^2 r_0^5}{Q^2} \right)^{1/3} \quad (11)$$

Therefore, using Eq. (10) and Eq. (11),

$$\Delta T \left( \frac{\rho^2 r_0^5}{Q^2} \right)^{1/3} \propto \left( \frac{z}{r_0} \right)^{-1} \quad (12)$$

Hence,

$$z \propto \frac{1}{\Delta T} \left( \frac{Q}{\rho r_0} \right)^{2/3} \quad (13)$$

If the temperature at the tip of the flame is given,

$$z \propto \left( \frac{Q}{r_0} \right)^{2/3} \quad (14)$$

and the height of external flame can be expressed as

$$z = \kappa \left( \frac{Q}{r_0} \right)^{2/3} \quad (15)$$

Figure 5 shows  $Q_{ef}/r_0$  on the horizontal axis and the height of the average flame tip  $z$  measured along the central axis of external flame on the vertical axis. This result suggests the validity of the relation of Eq. (14) although there are some deviations in the measured values. The value of  $\kappa$  in Eq. (15) can be calculated, by regression to the measured values, as

$$\kappa \approx 0.006 \quad (16)$$

By using dimensionless heat release rate  $Q^*$  expressed as

$$Q_{ef} = \rho_{\infty} c_p T_{\infty} g^{1/2} r_0^{5/2} \quad (17)$$

obtained by putting the amount of heat in external flame into dimensionless form, dimensionless temperature  $\Theta$  can be rewritten as

$$\Theta = \frac{\Delta T}{T_{\infty}} \propto \frac{1}{Q_{ef}^{2/3} \left(\frac{r_0}{T_{\infty}}\right)^{2/3}} \propto \frac{1}{Q_{ef}^{2/3} r_0^{2/3}} \quad (18)$$

From the above equation and Eq. (10), the following relation can be obtained:

$$Q_{ef}^{2/3} r_0^{2/3} \propto \left(\frac{z}{r_0}\right) \quad (19)$$

Substituting the opening width B for the representative length of fire source in deriving the dimensionless heat release rate, we obtain a rewritten form of Eq. (19):

$$Q_{ef}^{2/3} r_0^{2/3} \propto \left(\frac{z}{B}\right) \quad (20)$$

The results obtained from these relations are summarized in Fig. 6(a) and b). These results indicate that use of the opening width B, instead of the equivalent opening width  $r_0$ , makes the correlation between the dimensionless heat release rate and the height of the average external flame tip clearer. From the experiment results, the following regression equation can be obtained:

$$z = 0.65 Q_{ef}^{*2/3} B \quad (21)$$

### 3.4 Temperature of external flame

#### 3.4.1 Temperature distribution along the central axis of external flame

Applying the concept of buoyant flame in free space, Yokoi expressed temperature at the central axis of flame ejected from an opening by using the dimensionless temperature  $\Theta$  and the dimensionless height  $z/r_0$  (where the diameter of fire source is regarded as the equivalent opening radius,  $r_0$ , and  $z$  is the length of ejected flame along the central axis).<sup>18,19)</sup> According to Yokoi, in cases where there is a wall over the opening,  $\Theta$  and  $z/r_0$  approximately plot on a single curve, regardless of the aspect ratio of the opening.

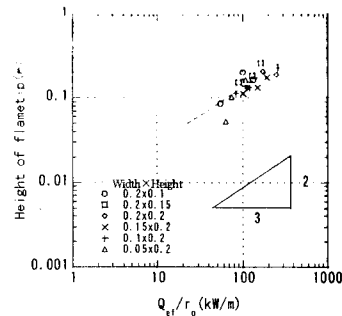
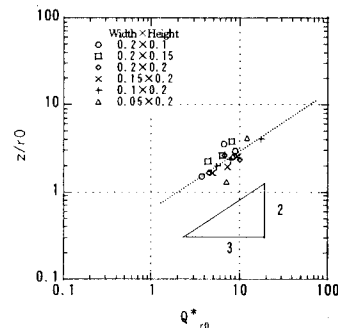
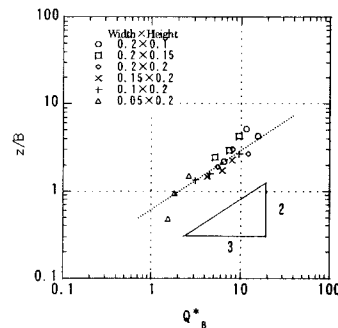


Fig.5 Relationship between  $Q_{ef}/r_0$  and height of averaged flame tip



$$a) D = (BH/2\pi)^{0.5}$$



$$b) D=B$$

Fig.6 Relationship between dimensionless heat release rate and height of averaged flame tip

Figure 7 shows the temperature distribution along the central axis of external flame, with the dimensionless temperature  $\Theta$  on the horizontal axis and the dimensionless height  $z/r_0$  on the vertical axis, as in Yokoi's results. The experiment results are shown so that values of  $Q_{ef}$  relative to  $AH^{1/2}$  are grouped, in ascending order, into Groups ① to ③, as shown in Fig. 3. According to these results, in cases where the heat release rate belongs to Group ①, plots approximately follow a curve representing Yokoi's experiment results. As the values of  $Q_{ef}$  increase, however, the experiment results tend to deviate from the lines representing Yokoi's experiment results.

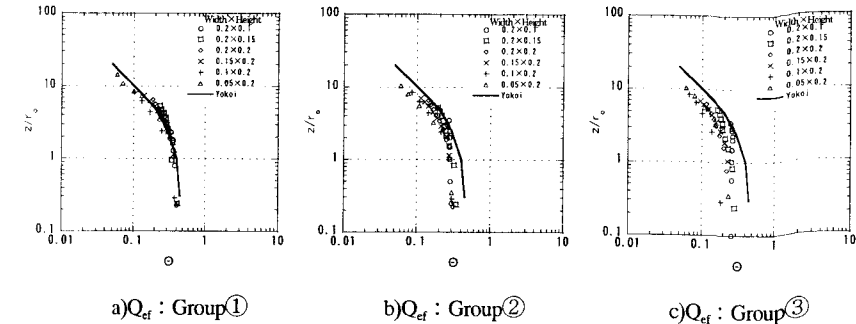


Fig.7 Temperature distribution along the central axis of external flame, with the dimensionless temperature  $\Theta$  and the dimensionless height  $z/r_0$

#### 3.4.2 Correction of temperature distribution along central axis of external flame

The method of using depth of virtual heat source as a correction value is already established as a means of predicting temperature distribution above a heat source in free space. In the present study, this approach is applied to flame projecting from an opening.

Figure 8 shows the relationship between a dimensionless parameter calculated by dividing the correction value  $\Delta Z$  by the equivalent opening radius  $r_0$  and the dimensionless heat release rate of ejected flame,  $Q_{ef}^*$ .  $\Delta Z$  is a parameter calculated so as to make the experiment data shown in Fig. 7 fit Yokoi's results. The dimensionless heat release rate of ejected flame  $Q_{ef}^*$  is calculated from the following equation.

$$Q_{ef}^* = \frac{Q_{ef}}{\rho_{\infty} c_p T_{\infty} g^{1/2} r_0^{5/2}} \quad (22)$$

From the experiment results shown in Fig. 7, the following equation for regression of the correction value  $\Delta Z$  can be derived:

$$\Delta z = 0.04 Q_{ef}^{*2} r_0 \quad (23)$$

Figure 9 shows the results obtained by correcting the experiment data shown in Fig. 7 by using Eq. (23). As can be seen from the results shown in Fig. 9, the experiment data have been corrected by  $\Delta Z$  so as to roughly fit Yokoi's results. Thus, by using the correction value  $\Delta Z$ , temperature distribution along central axis of external flame that correspond to the total heat releases rate  $Q_{ef}$  of external flame taking into consideration the combustion of excess fuel gas can be estimated, practically.

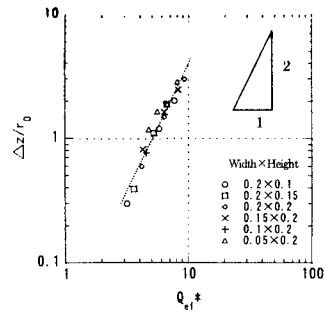


Fig.8 Relationship between  $\Delta z/r_0$  and  $Q_{ef}^*$

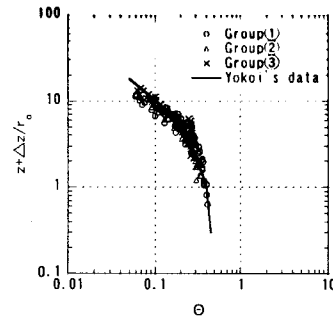


Fig.9 Experiment data corrected by  $\Delta z$

#### 4 Conclusions

Findings from this study can be summarized as follows:

1) Even at similar fire compartment temperatures and with similar thickness of external flames at an opening, dissipation of temperature from flames ejected from an opening and the height of flame may vary depending on the quantity of gas supplied to the gas burner. This is thought to be due to differences in the rate of heat released by fuel gas in the external flame.

2) The critical heat release rate  $Q_{crit}$  of external flame and the heat release rate  $Q_f$  due to the combustion of excess fuel gas under conditions where external flaming occurs tend to increase with the ventilation factor  $AH^{1/2}$ . Further, the critical heat release rate  $Q_{crit}$  shown in the form of the relationship between  $Q_{crit}/AH^{1/2}$  and  $A_T/AH^{1/2}$  roughly plot linearly.

3) Use of the width of opening instead of the equivalent opening radius to express a representative length of the fire source in the calculation of the dimensionless heat release rate makes the correlation between the length of external flame and the dimensionless heat release rate clearer. Dimensionless values obtained by dividing the height of the average flame tip measured along the central axis of external flame by the representative length of the external flame are approximately proportional to the two-third power of the dimensionless heat release rate.

4) A correction value  $\Delta z$  calculated from the dimensionless heat release rate, which is calculated from the total heat release rate of flame ejected from an opening, can be used to predict the temperature of external flame at its central axis, taking into consideration the combustion of excess fuel gas ejected from an opening.

The range of aspect ratio values for openings used in the experiment was chosen by reference to Yokoi's experiment conditions. It is necessary, therefore, to determine the scope of application of the proposed formula for calculating flame height and external flame temperature by applying it conditions that were not covered by the experiment. Applicability of the empirical formula derived from the small-scale fire tests to the full-scale fires is another

#### Nomenclature

A	:Area of opening(m <sup>2</sup> )
A <sub>T</sub>	:Total area of compartment boundary(m <sup>2</sup> )
B	:Opening width(m)
c <sub>p</sub>	:Specific heat of air(kJ/kgK)
g	:Gravitational acceleration(m/s <sup>2</sup> )
H	:Opening Height(m)
ΔH	:Heat of combustion per unit mass of fuel consumed(kJ/kg)
m <sub>f</sub>	:Amount of fuel gas ejected from opening(kg/s)
m <sub>c</sub>	:Amount of fuel gas generated in fire compartment(kg/s)
Q <sub>c</sub>	:Heat release rate of fire source(kW)
Q <sub>e</sub>	:Heat release rate convected out by opening flow(kW)
Q <sub>ef</sub>	:Total heat release rate of external flame(=Q <sub>e</sub> +Q <sub>f</sub> )(kW)
Q <sub>f</sub>	:Heat release rate to generate external flame from an opening(kW)
Q <sub>crit</sub>	:Critical heat release rate to generate external flame from an opening(kW)
Q <sub>Y</sub>	:Heat release rate of external flame defined by Yokoi(kW)
Q <sub>Y</sub> <sup>*</sup>	:Dimensionless heat release rate defined as Q/(ρ <sub>∞</sub> c <sub>p</sub> T <sub>∞</sub> g <sup>1/2</sup> r <sub>0</sub> <sup>5/2</sup> )
Q <sub>Y</sub> <sup>*</sup>	:Dimensionless heat release rate defined as Q/(ρ <sub>∞</sub> c <sub>p</sub> T <sub>∞</sub> g <sup>1/2</sup> B <sup>5/2</sup> )
R <sub>fo</sub>	:Rate of air outflow(kg/s)
R <sub>of</sub>	:Rate of air inflow(kg/s)
r <sub>0</sub>	:Equivalent opening radius(m)
T <sub>∞</sub>	:Ambient temperature(K)
T <sub>f</sub>	:Temperature in fire compartment(K)
z	:Height of flame(m)
Δz	:Depth of virtual heat source(m)
α	:Opening flow coefficient
γ	:Stoichiometric air/fuel ratio
Θ	:Non-dimensional temperature
ν	:Excess air ratio
Δρ	:Air density difference between air in fire compartment and ambient air(kg/m <sup>3</sup> )
ρ <sub>f</sub>	:Air density of air in fire compartment(kg/m <sup>3</sup> )

#### References

- 1)S. Yokoi: Japanese Ministry of Construction, Building Research Institute Report 34, 1960
- 2)American Iron and Steel Institute: Fire Safe Structural Steel - A Design Guide-, 1979
- 3)R.Jansson, B.Onnermark: Flame Heights Outside Windows, FOA Report, C 20445-A3, 1982.5
- 4)O.Sugawa, D.Momita, W.Takahashi: Flow Behavior of Ejected Fire Flame/Plume from an Opening Effectd by External Side Wind, Fire Safety Science, Proceedings of the Fifth International Symposium, pp249~260, 1996
- 5)Japanese Ministry of Construction: Total Fire Safety Design System of Buildings, Vol.2, The Building Center of Japan, 1989(in Japanese)
- 6)B.J.McCaffrey: Purely Buoyant Diffusion Flames : Some Experimental Results, NBSIR79-1910, 1979
- 7)F.R.Steward: Prediction of the Height of Turbulent Diffusion Buoyant Flames, Combustion Science and Technology,2 , pp203~212, 1970
- 8)G.Heskestad: Peak Gas Velocities and Flame Heights of Buoyancy-controlled Turbulent Diffusion Flames, 18<sup>th</sup> Symposium(International) on Combustion, pp951~960, 1981
- 9)Y.Hasemi, T.Tokunaga: Flame Geometry Effects on the Buoyant Plumes from Turbulent Diffusion Flames, Fire Science and Technology Vol.4 No.1, pp15~26, 1984

- 10) Y. Hasemi, M. Nishihata: Fuel Shape Effect on the Deterministic Properties of Turbulent Diffusion Flames, Bulletin of Japan Association for Fire Science and Engineering, Vol.38, No.2, pp1 ~ p8, 1989(in Japanese)
- 11) T. Tanaka: Introduction of Fire Safety Engineering, The Building Center of Japan, 1993(in Japanese)
- 12) C. Lin, S. Sugahara, T. Naruse: Emergence-limit of Flames from a Compartment opening –a though on some experimental results, Journal of Struct. Constr. Eng., AIJ, No.419, pp163~168, 1991.1(in Japanese)
- 13) B. Hagglund, R. Jansson, and B. Onnermark: Fire Development in Residential Rooms after Ignition from Nuclear Explosions, FOA Report C20016-D6(A3), 1974
- 14) R. Jansson, B. Onnermark: Fire Development in Residential Rooms after Nuclear Explosions, FOA Report C20445-A3, 1982
- 15) Y. Hasemi: Behavior of Ejected flame from a opening in Compartment Fire, Summaries of Safety Engineering Symposium, pp215~218, 1993.9(in Japanese)
- 16) P. H. Thomas: The Size of Flames from Natural Fires, Ninth Inter. Symp. Comb., pp844~859
- 17) S. Yokoi: On the Heights of Flames from Burning Cribs, Bull. of The Fire Prevention Society of Japan, Vol.13, No.1, pp22~27, 1963.6(in Japanese)
- 18) S. Yokoi: Temperature Distribution of Hot Air Current Issued from a Window of a Fire Resistive Construction in Fire, Bull. of The Fire Prevention Society of Japan, Vol.7, No.2, pp41~45, 1958.3(in Japanese)
- 19) S. Yokoi: Trajectory of Hot Gas spurting from a window of a burning Concrete House, Bull. of The Fire Prevention Society of Japan, Vol.8, No.1, pp1~5, 1958.6(in Japanese)

## Numerical Modeling of the Downward Flame Spread: The Effect of Opposed Forced Flow

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### ABSTRACT

The process of downward flame spread over the thin bed of combustible material is studied numerically by solving two-dimensional steady-state conservation equations. The algorithm for the prediction of flame spread rate is based on the principle of minimal entropy production. The primary purpose of investigation is focused on the influence of opposed ambient flow (forced and buoyancy) on the flame spread behavior. Achieved results showed the appropriate evaluation, in comparison with experimental data, of the overall effect of the opposed flow and of the limit of stable flame propagation.

**KEYWORDS:** Opposed flow, downward flame spread, numerical modeling

### NOMENCLATURE

*C* - Specific heat;  
*D* - Diffusion coefficient;  
*E* - Activation energy;  
*g* - Gravity acceleration;  
*J* - Thermodynamic flux;  
*k* - Preexponential factor;  
*L*<sub>0</sub> - Initial thickness of fuel bed;