Simple Method to Predict Downward Heat Flux from Flame to Floor

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ABSTRACT

This work presents a simple model to predict the radiation heat flux from a flame to a floor surrounding it. This heat flux was measured both in an unconfined space (open air) and under a ceiling. Flame lengths, flame temperatures, and ceiling surface temperatures, all of which are necessary to predict radiation heat flux, were also measured. Flame shapes were modeled by two cylinders and two disks representing the impinging flame’s continuous and intermittent flame regions. The emissivity of the cylinders was calculated from the heat balance at the flame surface, and the radiation heat flux to the floor was predicted well by the model.

Keywords: Radiation heat flux, Calculation method, Impinging flame, Ceiling jet

1. INTRODUCTION

Thermal radiation from a fire flame and a smoke layer will cause the fire to spread between combustible materials, even if they are located some distance apart. Therefore, the ability to accurately calculate the thermal radiation from the flames is important in predicting the spread of fire over combustible materials.

The radiation heat flux from a flame increases in proportion to the heat release rate (HRR) and decreases as the inverse square of the distance from the flame at a distance that is twice the diameter of the fire source [1]. However, a calculation method that considers the flame shape and temperature profile is more accurate near the fire source [2].

Heat flux to the downward-facing surface of a flat ceiling has been measured [3-4]; however, the heat flux to the floor directly beneath the ceiling has not been studied well. The purpose of this paper is to propose a simple method for predicting the radiation heat flux to the floor during fire impingement. Flame lengths and temperatures, which are essential to predict heat flux, were measured and compared with correlations from previous studies. Close examinations of flame lengths and flame temperature profiles were not performed because they were unnecessary for the purpose of this paper. The measured flame lengths and temperature profiles were used as inputs for the calculation of radiation heat flux.
2. EXPERIMENTS

2.1 Experimental Method

Schematic diagrams of the experimental setup are shown in Figure 1. The 2700 × 2700 mm-square unconfined ceiling and floor were made of 25-mm ceramic fiber board. The thermal properties of ceramic fiber board are shown in Table 1. The 250 × 250 mm-square gas burner was located at the center of the floor. City Gas 13A (methane 95%, ethane and propane 5%) was used as the fuel.

Temperatures in the region of the flame and ceiling jet were measured using 0.32-mm chromel-alumel thermocouples located 10 mm below the ceiling surface. The temperatures would be by 0.9 to 1.0 times of the maximum ceiling jet temperatures by experimental correlation [5] at the positions. The ceiling surface temperatures were also measured using 0.32-mm chromel-alumel thermocouples. The beads were set at the ceiling surface. The detailed positions of the thermocouples are shown in Figure 1.

The radiation heat flux to the floor was measured using heat flux gauges placed vertically upward at distances of 0.25–1.5 m away from the center of the burner. The locations of the heat flux gauges are shown in Figure 1(a). The temperatures and heat flux were recorded every one second by a data logger. The fuel supply rate to the burner was measured using a mass flow meter. The flame geometry was recorded with a digital video camera (30 frames/s).

Experiments were conducted in open air and under a ceiling. Ceiling heights, denoted by \( H \) in Figure 1(b), were varied to 360, 560, 760, and 1200 mm. The fuel supply rate was varied from 36 to 203 L/min as shown in Table 2, which this was done in a step-by-step manner, with each step lasting 5 min as shown in Figure 2. The temperature and heat
flux data used in the analysis were average values taken from data collected during the 4 min–to–4 min 30 s interval of each step. The HRR was calculated from the fuel supply rate by multiplying by the heat of combustion (41.549 kJ/L).

| Item                        | Value          |
|-----------------------------|----------------|
| thermal conductivity       |                |
| (400°C)                    | 0.09×10^{-3}   |
| (600°C)                    | 0.12×10^{-3}   |
| (800°C)                    | 0.16×10^{-3}   |
| (1000°C)                   | 0.21×10^{-3}   |
| density [kg/m³]            | 250            |
| specific heat [kJ/kg·K]    | 1.0*           |
| emissivity                 | 0.9*           |

*approximated value, not guaranteed by manufacturer

Table 2 Fuel supply rate, heat release rate (HRR), and dimensionless HRR

| Fuel supply rate $V_g$ [L/min] | 36  | 49.6 | 62  | 73.7 | 87  | 99.9 | 151.4 | 203 |
|--------------------------------|-----|------|-----|------|-----|------|-------|-----|
| Heat release rate $Q$ [kW]     | 24.9| 34.3 | 42.9| 51.1 | 60.3| 69.2 | 104.9 | 140.6|
| Dimensionless heat release rate $Q^*_D$ [-] | 0.71 | 0.98 | 1.23 | 1.46 | 1.73 | 1.98 | 3.01  | 4.03 |

$Q^*_D = Q/(c_p \rho \alpha T_g g^{1/2} D^{3/2})$

Figure 2 Heat release rate, the temperatures of the ceiling jet and the ceiling surface (at the measurement location shown in Figure 1) and Heat flux (H=1200)
2.2 Experimental Results

**Flame length**

Figure 3 shows the continuous flame length \( L_c \), which is the minimum length of the flame from the fire source in the 220 frames recorded by the digital video camera and the mean flame length \( L_m \), which is the average lengths, plotted against the dimensionless HRR \( Q_d* \) in an open air and in the case when the flame lengths are shorter than the ceiling height. The dimensionless HRR is calculated using the length of the side of the burner in place of \( D \). The experimental correlations proposed by Hasemi [6], as given in Equations 1 and 2, are also plotted in the figure.

\[
\begin{align*}
L_c/D &= 1.8Q_d^n \\
L_m/D &= 3.4Q_d^n
\end{align*}
\]

Where \( Q_d* = \frac{Q}{c_p \rho_\infty T_\infty g^{1/2} D^{5/2}} \), \( n = \frac{2}{3} (Q_d* \leq 1), n = \frac{2}{5} (Q_d* > 1) \)

![Figure 3](image)

**Figure 3** Comparison of measured and calculated flame lengths for flames smaller than ceiling height: \( L/D \) as a function of dimensionless heat release rate \( (Q_d*) \)

Mean flame length and continuous flame length are predicted by the correlations established in an open air. When there is a ceiling over the fire source, the flame length might differ from that in an open air because of the difference in entrainment rate. But the clear distinctions are not observed between two cases in this study.

Figure 4 shows the dimensionless mean flame radius, mean flame length \( L_m \) minus the ceiling height \( H \), plotted against the dimensionless HRR \( Q_d* \). The correlation proposed in the recent study [7] and the experimental results in earlier studies [3-4, 8-10] are also plotted. When the ceiling height is 760 mm and 560 mm, the flame radius were shorter than the data of earlier studies.
Figure 4  Comparison of measured and calculated flame radius for flames greater than ceiling height: 
\((L_m - H)/D\) as a function of dimensionless heat release rate \((Q^* D)\)

Figure 5 shows the dimensionless mean flame length plotted against the dimensionless HRR \(Q^*_DH\). The experimental correlation proposed by Yokobayashi [3] as given in Equation 3 and the data of earlier studies [3-4, 8-10] are also plotted in the figure.

\[
L_m/H = 2.58Q^*_DH^{2/5}
\]  \hspace{1cm} (3)

where \(Q^*_DH = Q/\left(c_p \rho_\infty T_\infty g^{1/2} DH^{3/2}\right)\)

When the ceiling height is 760 mm and 560 mm, the dimensionless mean flame lengths were slightly smaller than those in case of 360 mm ceiling height. But these data are predicted well by the correlation.

Figure 5  Comparison of measured and calculated flame lengths for flame heights greater than ceiling height: \(L_m/H\) as a function of dimensionless heat release rate \((Q^*_DH)\)
Figure 6 shows the continuous flame lengths and intermittent flame lengths $L_c$ which are the maximum lengths of the flame tips from the fire source, plotted against the mean flame lengths. The continuous flame lengths were 0.6 times the mean flame lengths. The intermittent flame lengths were 1.45 times the mean flame lengths. These correlations were independent of the relationship of the flame length to the ceiling height.

$L_c = 0.6L_m$

$L_i = 1.45L_m$

Figure 6 Continuous flame lengths ($L_c$) and intermittent flame lengths ($L_i$) versus mean flame lengths ($L_m$) for flame lengths ranging from less than to greater than ceiling height

Temperatures of ceiling jet

Figure 7 shows the dimensionless temperature rise of the ceiling jet, $\Delta T$, normalized by the temperature rise at the stagnation point ($\Delta T_p$). The distance from the stagnation point (directly above the center of fire source), $r$, was normalized by the plume radius at ceiling level, $b$, as proposed by Heskestad [8]. The experimental correlation proposed by Heskestad [8] is also plotted in the same figure. The experimental results recreated the same tendency with the Heskestad’s correlation, but the decrease of the temperatures is slightly smaller. The difference might be due to the difference in the thickness of ceiling materials. The thickness of the ceiling materials in this study is 25 mm and that in the previous study [8] is 12.7 mm.

$\Delta T/\Delta T_p$ versus $r/b$

Figure 7 Dimensionless temperature rise of the ceiling jet versus the dimensionless distance from the stagnation point
The correlation of the flame length and the temperature was examined. Figure 8 shows the temperature rise of the ceiling jet plotted against the distance from the fire source, \( r \), normalized by the mean flame lengths \( z = (H + r)/L_m \). Adjustment by virtual origin was not considered because temperatures were normalized by flame lengths. In the continuous flame region, temperature rise were almost constant at about 800 K. In the intermittent flame and plume regions, the temperature rise decay as \( z^{-6.5} \) and \( z^{-2} \), respectively. The correlations of the temperature rise in this study are described by Equation 4.

\[
\Delta T = T - T_\infty = \begin{cases} 
800 & z \leq 0.6 \\
430z^{-6.5} & 0.6 < z \leq 1.45 \\
570z^{-2} & 1.45 < z 
\end{cases}
\]  

(4)

\[ 
\begin{array}{c}
\text{Flame} \\
\text{Intermittent} \\
\text{Plume}
\end{array} 
\]

\[ 
\begin{array}{c}
\text{Lm}<H \\
\text{Lm} \geq H
\end{array} 
\]

Figure 8  Temperature rise in ceiling jet normalized by mean flame lengths \( (L_m) \) ranging from less than to greater than ceiling height \( (H) \)

Temperatures of ceiling surface

Figure 9 shows the temperature rise of the ceiling surface \( (\Delta T_c) \) plotted against the temperature rise of the ceiling jet \( (\Delta T) \). The temperature rise of the ceiling surface was 0.67 times the temperature rise of the ceiling jet of same radial position. This correlation is valid only for the same ceiling construction with this study. However, the thermal conductivity of the ceiling materials is smaller than that of ceiling materials used in common buildings. Thus the measured value could be an estimate of upper bound.
3. ANALYSIS

3.1 Calculation Methods of Radiation Heat Flux

Approximation of flame shape

Figure 11 shows the flame shape models used to predict the heat flux from the flame. Two methods are proposed. In the method 1, radiant emittance is uniformly distributed over the total area of the flame shape model. On the other hand, in the method 2, the
distribution of the radiant emittance is considered by dividing the flame shape model into two regions: continuous flame region and intermittent flame region.

In the method 1, when the mean flame length is shorter than the ceiling height, the flame shape is modeled by one cylinder, as shown in Figure 11 (upper left). The diameter of the cylinder is the same as the length of the side of the fire source, and their height is the same as the mean flame length.

When the mean flame length is longer than the ceiling height, the flame shape is modeled by the cylinder and a disk (see Figure 11, upper right). The radius of the disk is the radial length of the impinging flame, \( L_m - H \) (the mean flame length calculated by the Equation 3 reduced by the ceiling height) and the thickness is one-tenth of the ceiling height based on the thickness of the ceiling jet [5].

| Method 1 | \( L_c < L_m < H \) | \( L_c < H < L_m \) | \( H < L_c < L_m \) |
|---|---|---|---|
| ![Diagram](image1.png) | ![Diagram](image2.png) | ![Diagram](image3.png) |

| Method 2 | \( L_c < L_m < H \) | \( L_c < H < L_m \) | \( H < L_c < L_m \) |
|---|---|---|---|
| ![Diagram](image4.png) | ![Diagram](image5.png) | ![Diagram](image6.png) |

*Figure 11 Components of flame shape model used to predict heat flux from flame*

In the method 2, when the mean flame length is shorter than the ceiling height, the flame shape is modeled by two cylinders, as shown in Figure 11 (lower left). The diameter of the cylinders is the same as the length of the side of the fire source. Their heights are the same as the mean flame length and the continuous flame length. The upper part of intermittent flame region, which is between the mean flame length and the intermittent flame length is neglected because the temperature is low comparatively.

When the mean flame length is longer than the ceiling height and the continuous flame length is shorter than the ceiling height, the flame shape is modeled by the two cylinders and a disk (see Figure 11, lower center). The heights of cylinders are continuous flame length and ceiling height minus the thickness of disk. The radius of the disk is
the radial length of the impinging flame, \( L_m - H \) (the mean flame length calculated by the \textit{Equation 3} reduced by the ceiling height). The thickness of disk is one-tenth of the ceiling height based on the thickness of the ceiling jet [5].

When the continuous flame length is longer than the ceiling height, the flame shape is modeled by a cylinder and two disks depicted in Figure 11 (lower right). The height of cylinder is equivalent to the ceiling height minus the thickness of the disks. The radius of the disks is the radial length of the impinging flame \( L_m - H \) or \( L_c - H \) (the mean or continuous flame length reduced by the ceiling height). The thickness of the disks is one-tenth of the ceiling height.

\textbf{Flame length and flame temperature}

When the continuous flame length and mean flame length are shorter than the ceiling height, they are calculated by \textit{Equations 1 and 2}, respectively. When the length is longer, mean flame length are calculated by \textit{Equations 3} and the continuous flame length is taken by 0.6 times of the mean flame length based on the correlations shown in Figure 6.

The temperature of the cylinder in the method 2 is determined according to \textit{Equation 5}.

\[
T = \begin{cases} 
\frac{\Delta T_c + T_\infty}{4} + \sqrt{\frac{\Delta T_c + T_\infty}{4} + \frac{\Delta T_m + T_\infty}{4}} & \text{(Continuous flame region)} \\
\frac{\Delta T_c}{2} & \text{(Lower intermittent flame region)}
\end{cases}
\]

\textit{Equation 5}

Here, \( \Delta T_c \) is the temperature rise at the continuous flame length (= 800 K), determined according to the experimental correlation proposed by McCaffery [11]; \( \Delta T_m \) is the temperature rise at the mean flame length (= 500 K), determined in the same manner that \( \Delta T_c \) is determined; and \( T_\infty \) is the ambient temperature (= 293 K, 20°C). The temperature of the lower intermittent region is the average of the fourth power of the absolute temperature because it is used to calculate radiation heat flux. Based on \textit{Equation 5}, the temperature of the cylinder in the continuous flame region is 820°C (1093 K) and that in the intermittent flame region is 704°C (977 K).

The temperature of the disk is also determined according to \textit{Equation 5}. However, in this case, \( \Delta T_c \) is 800 K and \( \Delta T_m \) is 430 K, determined according to \textit{Equation 4}. Using these parameters in \textit{Equation 5}, temperature of the disk in the continuous flame region results in 820°C (1093 K) and the temperature of lower intermittent flame region results in 687°C (960 K).

\textbf{Radiant emittance}

When the mean flame length is shorter than the ceiling height, the balance of radiation heat flux would be described by \textit{Equation 6} was developed from the heat balance at the surface of the flame shape model:

\[
\chi Q = \sum \varepsilon_c A_c E_c
\]

\textit{Equation 6}

Here, \( \chi \) is the radiant fraction, \( \varepsilon \) is the emissivity, \( A_c \) is the surface area and \( E_c \) is the radian emittance of the cylinder.
In the method 1, radiant emittance is uniform and Equation 6 is transformed as follows

$$\varepsilon_c E_c = \frac{xQ}{A_c}$$  \hspace{1cm} (7)

In the method 2, Equation 6 is transformed as follows for the emissivity:

$$\varepsilon_c = \frac{xQ}{A_{cc}E_{cc} + A_{ci}E_{ci}}$$  \hspace{1cm} (8)

Here, $A_{cc}$ and $A_{ci}$ are the surface areas of the cylinders of the continuous flame region and intermittent flame region. $E_{cc}$ and $E_{ci}$ ($= \sigma T^4$, $E_{cc} = 81$ kW/m$^2$, $E_{ci} = 52$ kW/m$^2$) are the radiant emittance of the each region, which are calculated by the flame temperature as described above.

When the mean flame length is shorter than the ceiling height, the calculated results of the emissivity by the Equation 8 are shown in Figure 9 ($\chi = 0.2 - 0.4$). The surface areas and the radiant emittance of each region are calculated by the ways described above. They increase with HRR. The emissivity would actually increase with HRR because the mean beam length becomes longer.

![Figure 12 Calculated emissivity $\varepsilon_c$ versus HRR (D = 0.25m)](image)

When the mean flame length is longer than the ceiling height, the radiant emittance of the disks are assumed to be equal to the radiant emittance of the upper part of the cylinder which is higher than the ceiling height as shown in Figure 13.

$$\sum \varepsilon_c A^*_c E_c = \sum \varepsilon_d A_d E_d$$  \hspace{1cm} (9)

Here, $A^*_c$ is the surface area of the upper part of the cylinder which is higher than 0.9 times of the ceiling height, $A_d$ is the surface areas of the disk and $E_d$ are the radiant emittance of the disk.
In the method 1, radiant emittance is uniform and Equation 9 is transformed as follows:
\[ \varepsilon_d E_d = \frac{\varepsilon_c E_c \times A^*_{cc}}{A_{dc}} \]  \hspace{1cm} (10)

In the method 2, Equation 9 is transformed as follows for the emissivity:
\[ \varepsilon_d = \frac{\varepsilon_c (A^*_{cc} E_{cc} + A^*_{di} E_{di})}{A_{dc} E_{dc} + A_{di} E_{di}} \]  \hspace{1cm} (11)

Here, \( A^*_{cc} \) and \( A^*_{di} \) are the surface area of the upper part of the cylinder which are higher than 0.9 times of the ceiling height, \( A_{dc} \) and \( A_{di} \) are the surface area of the disk. \( E_{dc} \) and \( E_{di} \) \( ( = \sigma T^4, \sigma = 81\text{W/m}^2\text{K}^4, E_{dc} = 81\text{kW/m}^2, E_{di} = 48\text{kW/m}^2) \) are the radiant emittance of the each region, which are calculated by the flame temperature as described above.

Figure 13 Radiant emittance of the disk in method 2

**Heat flux to floor**

In the method 1, the radiation heat flux to the floor \( q'' \) was calculated from Equation 12:
\[ q'' = \varepsilon_c E_c \times F_c + \varepsilon_d E_d \times F_d + (1 - \varepsilon_d)(1 - \varepsilon_w)\varepsilon_d E_d \times F_d + (1 - \varepsilon_d)\varepsilon_w\sigma T^4_{w} \times F_d \]  \hspace{1cm} (12)

Here \( F_c \) and \( F_d \) are the shape factors of the cylinder and the disk relative to a target on the floor surface. These are calculated by the way shown in Figure 14. The third term denotes the radiation heat flux emitted by the disk and reflected at ceiling surface heated by disk. For a wide range of surface emissivity of ceiling, the third and fourth terms compensate each other. In addition, the shape factors of disk and hot ceiling would be almost identical. Thus it is reasonable to put
\[ (1 - \varepsilon_d)(1 - \varepsilon_w)\varepsilon_d E_d \times F_d + (1 - \varepsilon_d)\varepsilon_w\sigma T^4_{w} \times F_d \approx (1 - \varepsilon_d)\varepsilon_d E_d \times F_d \]  \hspace{1cm} (13)

Putting Equation 13 to 12, we get
\[ q'' = \varepsilon_c E_c \times F_c + (2 - \varepsilon_d)\varepsilon_d E_d \times F_d \approx \varepsilon_c E_c \times F_c + 2\varepsilon_d E_d \times F_d \]  \hspace{1cm} (14)

The right equation is conservative assumption of the middle equation.
In the method 2, the radiation heat flux to the floor $q''$ was calculated from \textit{Equation 11}:  

$$q'' = \varepsilon_c (E_{cc} F_{cc} + E_{cel} F_{cel}) + (1 - \varepsilon_d) \varepsilon_w \sigma T_w^4 + (1 - \varepsilon_d) \varepsilon_w \sigma T_i^4$$  

(11)

Here, $\varepsilon_w$ is the emissivity of the ceiling surface (=0.9) and $T_w$ is the temperature of the ceiling surface calculated by the experimental correlation ($\Delta T_w=0.67 \Delta T$) as shown in \textit{Figure 9} and $T$ is the flame temperature of the disk of the each region as shown in \textit{Figure 11}.

| Cylinder | Disk |
|----------|------|
| ![Cylinder diagram](image) | ![Disk diagram](image) |
| $h$: Cylinder height | $h$: Vertical distance from the disk to the target |
| $r_1$: Cylinder radius | $r$: Disk radius |
| $r_2$: Horizontal distance from the center of the cylinder to the target | $a$: Horizontal distance from the center of the disk to the target |

$$R = r_1 / r_2, \quad L = h / r_2, \quad X = \left(1 + L^2 + R^2\right)^{1/2}$$

$$F_{d1-2} = \frac{1}{2\pi} \tan^{-1} \left( \frac{R}{\sqrt{1 - R^2}} \right) - 1 + L^2 - R^2$$

$$F_{d1-2} = \frac{1}{2} \left[ 1 - \frac{1 + H^2 - R^2}{\sqrt{Z^2 - 4R^2}} \right]$$

\textit{Figure 14} Formulas for shape factors [12]

\section*{3.2 Calculation Results}

\textit{Open air}  

\textit{Figure 15(a)} shows the measured and calculated heat flux to the floor at HF4 (the distance from the center of fire source $L$ is two times of the length of the side of the fire source, D) and HF6 (the distance from the center of fire source $L$ is equal to D) in open air plotted against the heat release rate. The experimental tendency for heat flux to the floor to increase with HRR is predicted well by the methods when $L$ is equal to 2D. The calculated values by method 1 are lower than method 2 when $L$ is equal to $D$. \textit{Figure 15(b)} and (c) show the calculated values of heat flux to the floor surface in open air by method 1 and method 2 plotted against the measured values. The experimental results are predicted well in the whole when radiant fraction $\chi$ is 0.35.
Figure 15  Comparison of calculated and measured Heat flux to floor in open air ($\chi=0.35$)

**Under ceiling**

The radiant fraction is set as 0.35 based on the comparison between the experimental and the calculated result of the radiation heat flux in an open air.

*Figure 16* shows a plot of the measured and calculated values of the heat flux to the floor surface versus the HRR at 250 mm and 500 mm away from the center of the fire source when the ceiling height is 760 mm. The method 1 predicts the experimental results well except when the continuous flame length is greater than the ceiling height. The method 2 recreates the experimental tendency in the whole but it overestimates the experimental results slightly.
Figures 17 to 19 show the calculated values plotted against the measured values of heat flux to the surface of the floor for various relationships between the flame length and the ceiling height; all figures are for the ceiling case.

As shown in Figure 17, the calculated value by method 1 and method 2 tend to be generally a little lower than the measured value when the ceiling height is higher than the mean flame height. This is because the heat flux from the portion of the ceiling warmed up by the ceiling jet is not considered in the calculations. This makes the difference larger, especially when the value of the heat flux is low.

When the ceiling height is higher than calculated the continuous flame length and lower than the calculated mean flame length, Figure 18(a) shows that the measured value is predicted well by the method 1 in the whole but is underestimated slightly near the
fire source as shown in the dashed circle. Figure 18(b) shows that the measured value is overestimated slightly by the method 2.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure18.png}
\caption{Comparison of heat flux to floor when ceiling height is higher than calculated continuous flame length and lower than calculated mean flame length ($L_c < H < L_m$)}
\end{figure}

As depicted in Figure 19, the calculated value is in good agreement with the measured value when the ceiling height is lower than the calculated continuous flame length. But the measured value are underestimated by the method 1 especially at HF1,4 ($L = 500\text{mm}$) and HF2 ($L = 250\text{mm}$) as shown in the dashed circle. The distance from fire source $L$ is smaller than the mean flame radius of these data. This is because the distribution of radiant emittance is not considered in the method 1. Therefore the method 2 is recommended in case when the distance from the fire source is smaller than the mean flame radius.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure19.png}
\caption{Comparison of heat flux to floor when ceiling height is lower than calculated continuous flame length ($H < L_c < L_m$)}
\end{figure}
4. CONCLUSIONS

The heat flux from a flame to the floor surface below it, as well as the flame length and temperatures, were measured in open air and below a ceiling. A simple method was then proposed to predict the downward heat flux to the floor surface. The flame length was predicted well by the dimensionless heat release rate calculated using the previous correlation. Correlations of the temperatures of the impinging flame and ceiling jet with the distance from the fire source were proposed.

Flame shapes were modeled by two cylinders and two disks to represent the different conditions for the impinging flame, which is composed of a continuous flame region and an intermittent flame region. The emissivity of the cylinders was calculated from the heat balance at the flame surface. The radiation heat flux to the floor was predicted well by the model when the mean flame length and continuous flame length were longer than the ceiling. But when the mean flame length was shorter than the ceiling, the calculation results was underestimated a little because thermal radiation from the warmed ceiling was ignored. The accuracy of the prediction of heat flux depends on the accuracy of the prediction of the flame length and the radiant fraction.

NOMENCLATURE

Alphabets

- $A$: area of the surface [m$^2$]
- $c_p$: specific heat of air at constant pressure [kJ/kgK]
- $D$: diameter of fire source [m]
- $E$: radiant emittance [kW/m$^2$]
- $F$: shape factor [-]
- $g$: acceleration of gravity [m/s$^2$]
- $H$: ceiling height [m]
- $L$: distance from the center of the fire source [m]
- $L_c$: continuous flame length [m]
- $L_m$: mean flame length [m]
- $L_i$: intermittent flame length [m]
- $Q$: heat release rate [kW]
- $Q_{D}$: dimensionless heat release rate calculated using the length of the side of the burner [-]
- $Q_{DH}$: dimensionless heat release rate calculated using the length of the side of the burner and the ceiling height [-]
- $T$: temperature [K]
- $V_g$: fuel supply rate [L/min]

Greek letters

- $\chi$: radiant fraction [-]
ε : emissivity [-]
ρ : density [kg/m³]
σ : stefan-Boltzmann constant [kW/m²K⁴]

Subscripts

c : continuous flame region, cylinder
d : disk
f : flame
i : intermittent flame region
∞ : ambient air

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