FLAME HEIGHTS AND HEAT FLUXES ON A BUILDING FACADE AND AN OPPOSITE BUILDING WALL BY FLAMES EMERGING FROM AN OPENING

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ABSTRACT

An opening in a fully developed burning room is the main path of a fire spreading from floor to floor and to an adjacent building. Even though the issue of fire spread to an adjacent building has been incorporated in fire safety engineering design guidelines, a performance-based design provides an alternative and accurate method to optimize the distance between the burning building façade and an adjacent building. This situation was simulated by performing a series of small–scale experiments having a façade wall with flames and an opposite parallel wall representing an adjacent building in order to investigate the physics of the flame behaviour and measure the heat fluxes between two walls. The outcome of this research provides unique information for engineering design for separation distances between adjacent buildings. A new length scale, ℓ_3, representing the length after which the flames turn from horizontal to vertical was developed in this research. The significance of this length scale has been verified by the experimental results for flame heights and heat fluxes and by observations. A similarity correlation for flame heights between the two parallel walls were developed in this research. Similarity correlations for radiative heat fluxes on facade walls were developed by dividing the data into two groups. One is for the distance between two walls being larger than length scale ℓ_3, the other is for the distance being less or equal to length scale ℓ_3.

KEYWORDS: Flame heights, Heat flux, Façade, Opposite wall, Length scale

INTRODUCTION

A considerable effort has been exerted to investigate the temperature distribution in external flames as well as flame heights and heat fluxes in external façade from a burning enclosure [1-5]. Little research has been directed in investigating the flame behaviour in the vicinity of the opening and between a building having a burning enclosure and an adjacent building. This fire scenario is different from single façade fires since the external combustion can be controlled by entrainment from the side of two walls when the separation is small. Some research has been conducted to investigate heat fluxes (and flame heights) between parallel walls by mounting a gaseous burner at the base between two parallel walls to study the warehouse fire scenario where the vertical channels between adjacent stacks offer an ideal pathway [6-7]. The burning for these experiments is similar to the fire scenario investigated in this research because both of them can be influenced by the amount of air entrained from the side of two walls. However, the behaviour of flames issuing from a line burner at the base between two walls does not represent exactly flame ejecting from the opening of a burning enclosure, since the flames from an enclosure are ejected horizontally before they turn upwards. In addition, the flammable gases ejected from an opening have been preheated in the enclosure whereas the upward flammable gas from a line burner at the base between two walls is supplied at ambient temperature. Therefore, the soot tendency in the ejected flames from the opening could be higher than those from the line burner[8] which might cause a higher level of heat transfer to walls from flames ejected from the opening of a burning enclosure. Lougheed and Yung conducted experiments to investigate the fire exposure to adjacent structure due to fire plums issuing from a burning enclosure[9]. However, there are no flame height measurements and correlation of heat fluxes in their work. In this paper, small-scale experiments consisting of a burning enclosure with a façade wall and a parallel opposite wall were conducted to examine the impact of various opening geometries, fire supply rate and distance between the façade wall and parallel opposite wall on the flame heights and heat exposure to both walls. A new length scale, which is capable of physically describing flame behaviour in the vicinity of the opening, was developed for under-ventilated enclosure fires (see Appendix). Correlations for flame heights and heat fluxes on façade using the new length scale were developed in this research.

EXPERIMENTAL SET-UP AND PROCEDURE

The experimental model (see Figs. 1 and 2) was made of fiberboard walls having dimensions 0.5 m by 0.5 m by 0.5 m. The openings at the front face were centred of door configuration and had the following widths and heights: 0.1 m × 0.25 m, 0.2 m × 0.2 m and 0.25 m × 0.1 m. The external façade and a parallel wall opposite to the façade having various distances, D, from 0.1 m to 0.5 m were made of fiberboard plates as shown in Fig. 1. Fig. 2 shows the front view of the façade and the opposite wall. A propane rectangular sandbox burner located at the center of the model compartment was the fuel source with the fuel supply rate regulated by a mass flow controller. The experiments were designed to produce ventilation controlled fires by controlling the mass flow rate of the fuel to be larger than the fuel needed for stoichiometric combustion of the air entering into the enclosure which corresponds to a heat release rate of $1500\,A\sqrt{H}$ (kW) inside the burning enclosure (here A and H are the area and height of the opening of the enclosure expressed in meters). This value has been confirmed in previous research for the case without a parallel wall opposite to the opening of burning enclosure [5]. The experimental tests and conditions are summarised in Table 1.

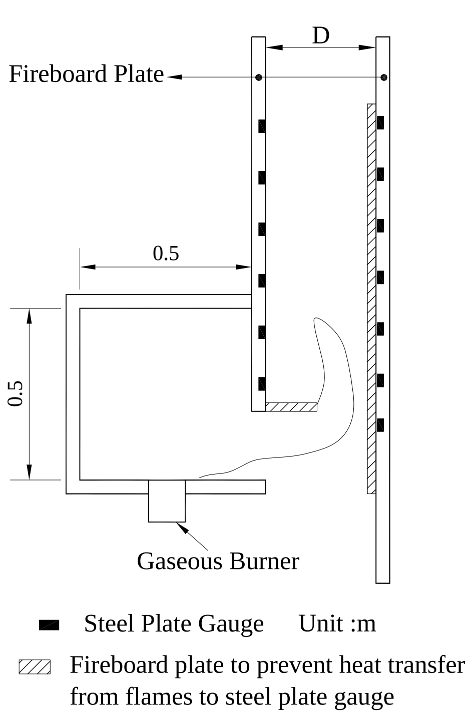


FIGURE 1. The sketch of experimental enclosure, façade wall and opposite wall

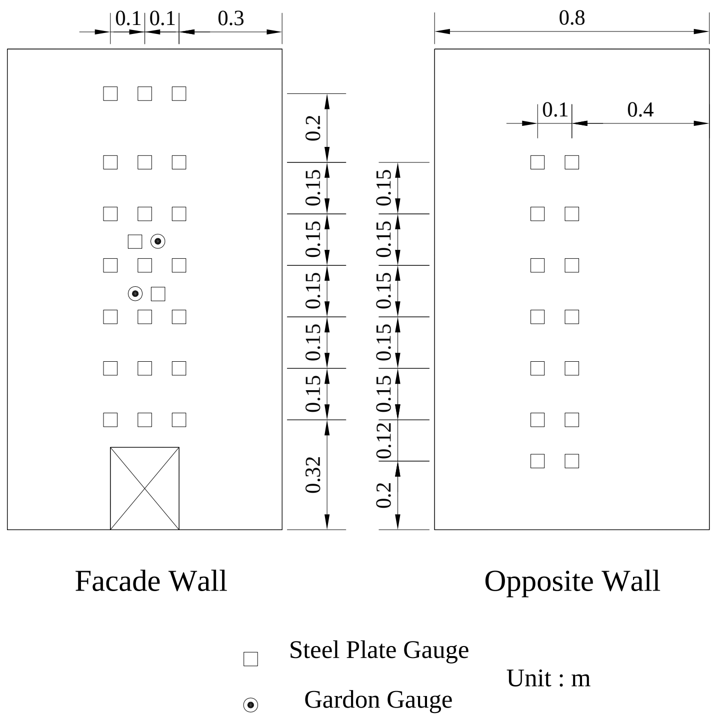
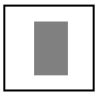


FIGURE 2. The front view of façade wall and the opposite wall with their instrumentation

TABLE 1. Experimental conditions (∞: for the experiment without opposite wall)

Burner Location	Opening Dim.		Heat Release Rate (kW)	Distance Between Two Walls (m)
	W (m)	H (m)		
	0.1	0.25	40	0.1 0.2 0.3 0.4 0.5 ∞
	0.2	0.2	50	
	0.25	0.1	20	

The measurements included:

1. Gas temperatures were measured inside the enclosure by thermocouple trees at two diagonal corners inside the enclosure (not shown here)
2. Flame heights were measured by a CCD camera facing the side of the two walls using a validated image-processing technique to map the probability of flame presence and determine the extent of the external combustion (see Fig. 3) [5, 10-11].
3. The total heat fluxes in the façade were measured by small steel heat flux gauges. This apparatus (steel plate gauge) with thermocouples spot-welded to the back of the steel plate has been employed for heat flux measurement in previous façade fires research [5]. Fig. 4 shows the details of the steel plate gauge. The steel plate gauge with dimensions 25 mm by 25 mm by 3mm was employed in this work to measure total heat fluxes in two walls.

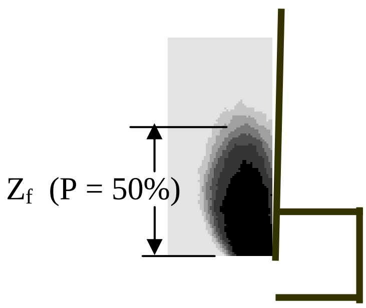


FIGURE 3. Probability of presence of flame and flame regimes for the fires between two walls using a CCD camera ("P" represents flame presents probability)

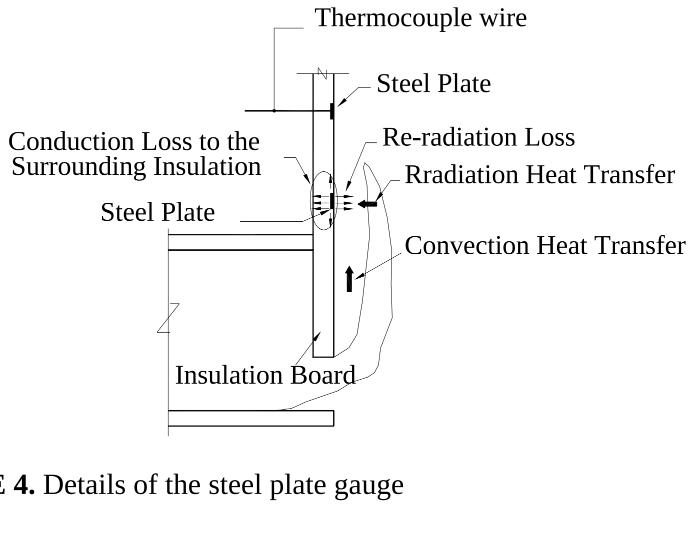


FIGURE 4. Details of the steel plate gauge

The experimental procedure was designed to establish steady state conditions inside the enclosure in the following way:

a) The flow rate of the fuel was increased at a fixed rate after its ignition until the desired flow (or theoretical heat release rate) was reached, and the gas temperatures in the enclosure was quasi-steady.

b) During this period, the following experimental procedure was conducted to prevent the flames from impinging on the façade and the opposite wall and imposing a heat flux on the steel plate gauges in either wall before steady conditions occurred.

b1. For the case with $D \geq 30cm$

A horizontal fiberboard plate was placed over the opening of the façade wall to deflect the flames from the façade wall and a fireboard plate was vertically attached in front of the opposite wall to prevent the heat transfer from flames to the steel plate gauge in both walls (see Fig. 1).

b2. For the case with $D < 30cm$

Because the gap between two walls is small, it is difficult to remove the fireboard attached on the opposite wall; only a horizontal fiberboard plate was placed over the opening between the façade and the opposite wall (see Fig. 1).

c) The horizontal fibreboard above the opening of the burning enclosure and the vertical fireboard attached on the wall opposite to the façade wall were removed after steady conditions were established in the enclosure and the flames were now attached to the façade and opposite wall exposing the heat flux gauges suddenly to the heat flux from the flames. This procedure allows determination of the total heat fluxes from the recorded steel plate temperature using only the storage energy term because the other terms, i.e. convection correction, reradiation, and conduction into the insulation are negligible (see Fig. 4) [5] .

EXPERIMENTAL RESULTS

To investigate the effect of distance between two walls on the behaviour of ejected flames in the vicinity of the opening, a length scale representing the length after which the flames turn from horizontal to vertical due to buoyancy was developed as outlined in the Appendix. This length scale can explain the physical behaviour of flames. The discussion of experimental results for the flame heights and heat fluxes exposed on both walls are presented as below.

Flame Heights between Two Walls

Fig. 5 shows the experimental results of flame heights against the distance between two walls for experiments with various opening geometries. Table 2 shows the values of length scale ℓ_3 calculated by Eq. [A6] for the three opening sizes.

By inspecting Fig. 5 using the length scales shown in Table 2, it can be observed that the flame heights for the tests without opposite wall are quite consistent with those having distance between two walls (D) and are larger than their corresponding length scale ℓ_3. However, the flame heights were suddenly increased for each opening geometry test when the distance between two walls is less than their corresponding length scale ℓ_3. This occurs because the ejected flames impinge on the opposite wall when $D \leq \ell_3$ which causes higher flame heights compared with those having $D > \ell_3$.

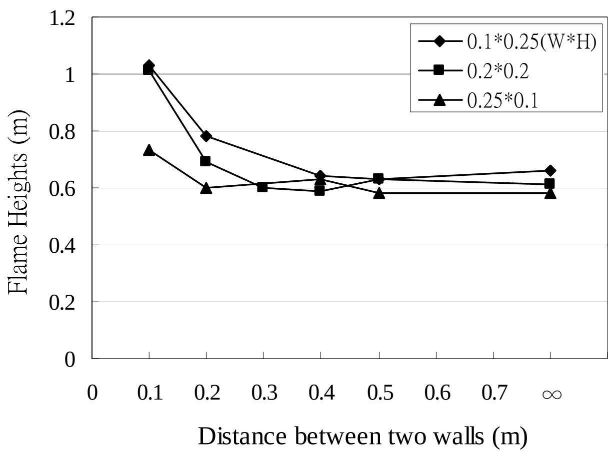


FIGURE 5. Experimental flame heights for tests with different opening size and various distances between two walls

TABLE 2. Value of length scale ℓ_3 for different opening geometry

Opening Geometry (W*H m)	Length scale $\ell_3 = (AH^{4/3})^{3/10}$ m
0.1*0.25	0.19
0.2*0.2	0.2
0.25*0.1	0.13

Heat Fluxes on Façade Wall and Opposing Wall

Fig. 6 shows the heat flux distributions along the certerline above the opening on façade wall and on the opposite wall against the value of Z/Z_f for the experiments having various opening geometries and distance between two walls. Here, Z and Z_f are the locations of steel plate gauge and the measured flame height. Both of them are measured from the position of neutral plane which is 0.4 H (H is the height of the opening) above the bottom of the opening [5]. The off-center heat flux distributions on two walls are not presented in this paper because of lack of space. Similar observations like in the discussion on flame heights can be made regarding the heat flux measurements on the façade and the opposite wall as shown in Fig. 6 where the heat flux measurements increased suddenly for the case having $D \le \ell_3$. The physical meaning of length scale ℓ_3 was also confirmed by the experimental observation. It is found that the outer region of the ejecting flames are impinging on the opposite wall when the distance between two walls is very close to the length scale ℓ_3 regardless of the opening geometry in the experiments.

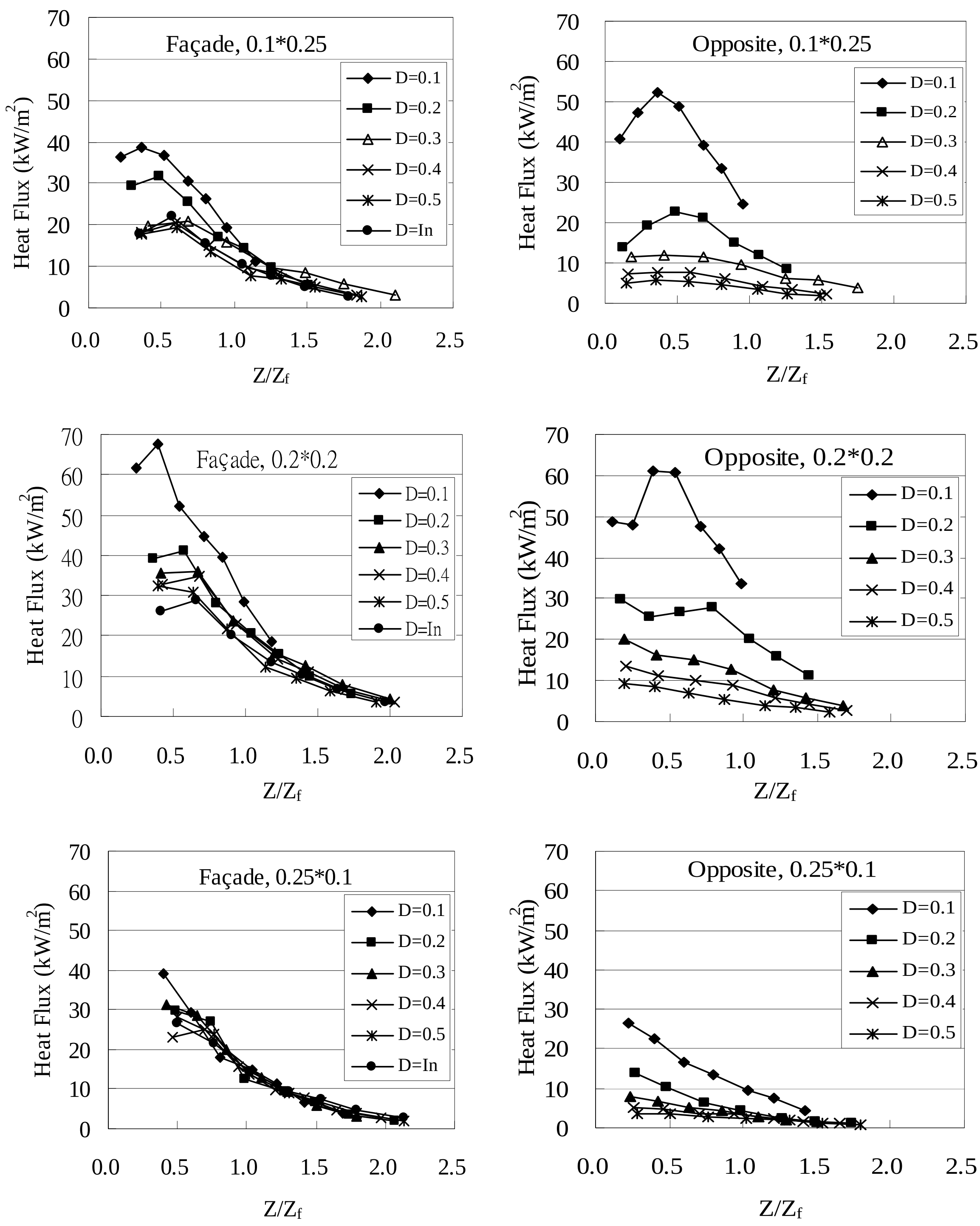


FIGURE 6. Heat flux distribution along the centreline above the opening on façade wall and on the opposite wall (D = In: for the case without opposite wall)

ANALYSIS OF EXPERIMENTAL RESULTS

The correlation of flame heights and heat fluxes on façade are presented as below.

Flame Heights between Two Walls

Based on the discussion above, not only the distance between two walls but both the height and width of the opening which are incorporated in the equation of ℓ_3 (see Eq. [A6]) and the heat released outside the enclosure ($\dot{Q}_{ext}$) will affect the burning outside the enclosure [3,5]. From dimensional analysis, the flame height could be determined by:

$$\frac{Z_f D^{2/3}}{\left(\frac{\dot{Q}_{ext}}{\rho_\infty c T_\infty g^{1/2}}\right)^{2/3}} = \mathrm{fcn}\left(\frac{D}{\ell_3}\right) \quad [1]$$

$$\dot{Q}_{ext} = \dot{Q}_{th} - 1500 A H^{1/2} \quad [2]$$

where $\dot{Q}_{th}$ is the heat release rate calculated by the fuel supply rate of the burner, D is the distance between two walls, ρ_∞ and T_∞ are the density and temperature of ambient air, respectively.
Fig. 7 verifies the correlation of flame height using Eq. [1].

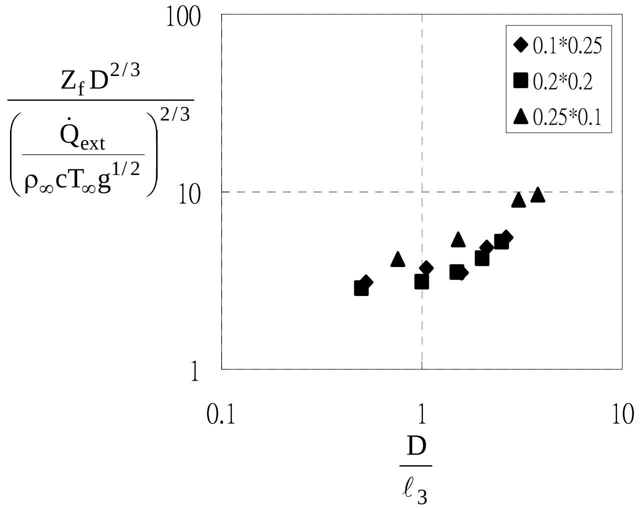


FIGURE 7. Correlation of flame height between two walls

Heat Fluxes on Façade Wall

Based on dimensional analysis, the following general function is applied for the correlation of heat flux on façade:

$$\frac{\dot{q}''_t Z_f}{\dot{Q}_{ext}/\ell_3} = \mathrm{fcn}\left[\frac{Z}{Z_f}, \frac{Z_f}{\ell_3}, \frac{\ell_3}{\ell_1}, \frac{\ell_3}{D}\right] \quad [3]$$

where ℓ_1 is the length scale representing the exit condition of the burning enclosure (see Appendix), and $\dot{q}''_t$ is the total heat flux to the façade wall.

Based on Eq. [3] and the fact that the two length scales ℓ_1 and ℓ_3 are almost equal, two groups of correlation were employed in this research. The correlation functions and their corresponding correlation figures were presented below:

1. For the case of $D > \ell_3$, the correlation function is proposed as below:

$$\frac{\dot{q}_t'' Z_f}{\dot{Q}_{ext} / \ell_3} \cdot e^{0.6\left(\frac{\ell_3}{\ell_1}\right)^{5.5}} = \text{function}\left(\frac{Z}{Z_f}\right) \qquad [4]$$

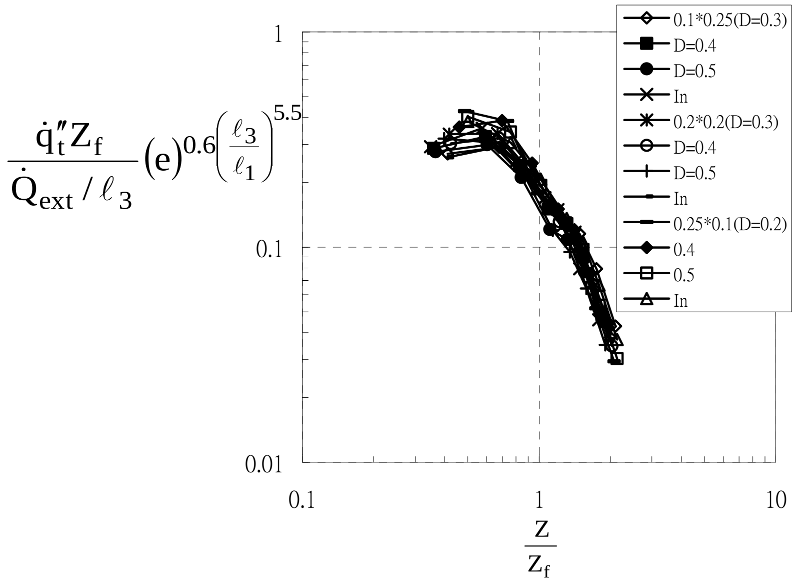


FIGURE 8. Correlation of heat flux at the centreline above the opening on façade wall for the experiments having $D > \ell_3$. ("In": for the case without opposite wall)

2. For the case of $D \le \ell_3$, the correlation function is expressed as:

$$\frac{\dot{q}_t'' Z_f}{\dot{Q}_{ext} / D} \cdot e^{0.6\left(\frac{\ell_3}{\ell_1}\right)^{5.5}} = \text{function}\left(\frac{Z}{Z_f}\right) \qquad [5]$$

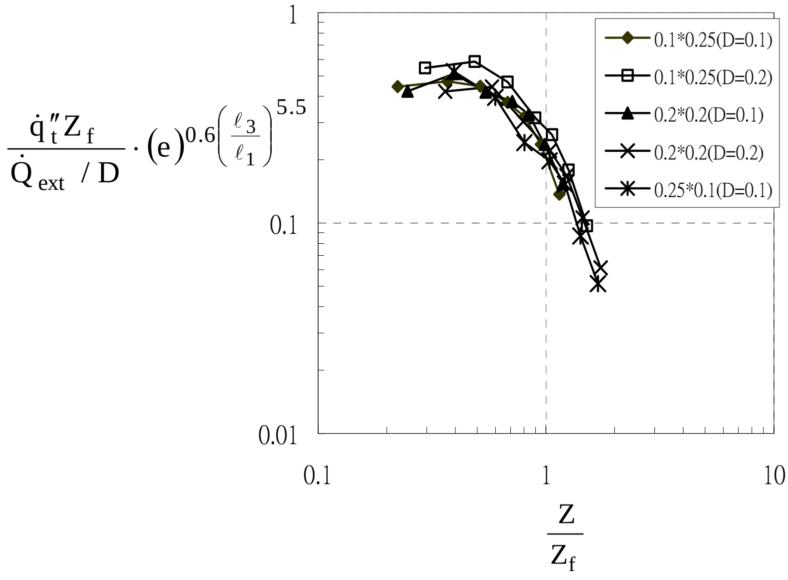


FIGURE 9. Correlation of heat flux at the centreline above the opening on façade wall for the experiments having $D \le \ell_3$

Complete explanation of this behaviour in Fig. 9 is not yet available.

CONCLUSIONS

1. A new length scale ℓ_3 was developed in this research representing the length after which the flames turns from horizontal to vertical from the opening of a burning enclosure.
2. The physical meaning of the length scale has been confirmed by experimental results and observations in this research, namely for separation distances greater than this length scale the flow and heat fluxes are not affected by distance between the walls. This result provides a rational design method for the separation distances between buildings.
3. A similarity correlation of flame height between two walls was presented in Fig. 7.
4. The heat fluxes imposed on the external walls were correlated using two length scales ℓ_1 and ℓ_3. The former represents the exit condition of a burning enclosure and the latter represents the length after which the flames turns from horizontal to vertical. The correlations consist of two groups, one is for the cases having distance between two walls larger than ℓ_3 (see Eq. [4] and Fig. 8), the other is those having distance between two wall less or equal to ℓ_3 (see Eq. [5] and Fig. 9).

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APPENDIX

Length Scales Representing the Length after which the Flames Turns from Horizontal to Vertical

A length scale for the under-ventilated fires with flame ejecting outside the opening representing the length after which the flames turns from horizontal to vertical due to buoyancy (ℓ_3), are presented below. The horizontal length after which the flames become vertical can be determined by the competition of momentum and buoyancy in the vicinity of the opening. Fig. 8 shows the sketch of the variables for deriving the length scale ℓ_3.

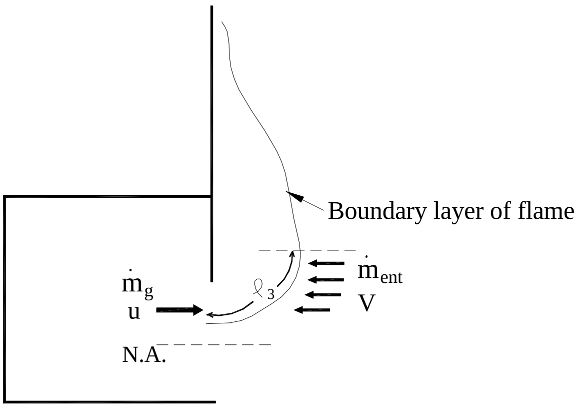

FIGURE A1. The sketch of the variables for deriving length scale ℓ_3

The upward momentum due to the entrainment can be expressed as:

$$M_{ent} \propto \rho_\infty \left(\sqrt{\frac{\Delta T_f}{T_\infty} g \ell_3} \right) \ell_3 \ell_1 \left(\sqrt{\frac{\Delta T_f}{T_\infty} g \ell_3} \right) \qquad [A1]$$

where ΔT_f is the temperature rise between flame and ambient; ρ_∞ and T_∞ are the density and temperature of ambient air, respectively; ℓ_3 is the distance of flames ejecting from the opening after from horizontal to vertical; and $\ell_1 = \left(AH^{1/2}\right)^{2/5}$ is the length representing the exit condition of the enclosure [5].

The horizontal momentum flux at the exit M_0 is equal to:

$$M_0 \approx \rho_g \frac{\Delta T_g}{T_\infty} \left(H - Z_o\right)^2 gW \qquad [A2]$$

where W is the width of the opening, ΔT_g is the temperature rise between gas inside the enclosure and ambient, and Z_o is the distance between the neutral plane and bottom of the opening.

The characteristic length ℓ_3 after which buoyancy dominates is defined by equating the horizontal momentum at the origin (Eq. [A2]) with the vertical momentum (Eq. [A1]) generated by the buoyancy

$$M_{ent} = \rho_\infty \frac{\Delta T_f}{T_\infty} g \ell_3^{\,2} \ell_1 \approx \rho_g \frac{\Delta T_g}{T_\infty} (H - Z_o)^2 gW = M_0 \qquad [A3]$$

Inserting $\ell_1 = (AH^{1/2})^{2/5}$ in Eq. [A3] and making arrangement, it gives:

$$\ell_3 \propto \left(\frac{\Delta T_g}{\Delta T_f}\right)^{1/2} \left(\frac{\rho_g}{\rho_\infty}\right)^{1/2} \left(1 - \frac{Z_o}{H}\right) \left(AH^{4/3}\right)^{3/10} \qquad [A4]$$

In the case of under-ventilated fire condition, Eq. [A4] can be expressed as [13] :

$$\ell_3 \propto \left(\frac{\Delta T_g}{\Delta T_f}\right)^{1/2} \left(\frac{\rho_g}{\rho_\infty}\right)^{1/2} \left(1 - \frac{1}{1 + \left(\frac{\rho_\infty}{\rho_g}\right)^{1/3}}\right) \left(AH^{4/3}\right)^{3/10} \qquad [A5]$$

In under-ventilated fire, the effect of enclosure gas temperature and temperature of flames (assume $\Delta T_f \approx 2000K$) on the length scale ℓ_3 was examined by the cases having gas temperature 600^{o}C and 1000^{o}C, respectively. It is observed that the length scale ℓ_3 is independent on the gas temperature inside the enclosure for the case of under-ventilated fire condition. Thus, the length after which the flames turn from horizontal to vertical for the case with flames appear outside of the enclosure can be expressed as:

$$\ell_3 \propto (AH^{4/3})^{3/10} \qquad [A6]$$