Enclosure and Facade Fires: Physics and Applications

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ABSTRACT

Facade fires being a disastrous hazard for high rise building, as several historical and recent incidents have shown, have attracted the interests of numerous fire scientists, engineers and regulators. This work has as an objective to present issues in this area that are challenging and need further attention. It focuses on characterizing the flame height and heat fluxes from facade flames produced from under-ventilated enclosure fires on a facade that is not flammable. Such an investigation is an important consideration for practical applications as well as a prerequisite for examining fire spread on flammable facades and for designing a test for modern facade assemblies. The mass pyrolysis rates and burning of real fuels are discussed in under ventilated enclosures, rectangular or corridor like, for various openings presenting the current state and some critical issues. Facade flames are analyzed from experiments using gaseous burners to have control on the fuel supply rate by introducing physical length scales for the opening geometries to model flame heights and heat fluxes. An important parameter for the facade flames is the excess heat release rate of the fuel burning outside the enclosure. Finally, applications for facade flames with sidewalls and facade flames from two openings are presented.

KEYWORDS: enclosure fires, facade flames, excess heat release rates, flame heights, heat fluxes

INTRODUCTION

It is a difficult task to provide due credit to previous work related to enclosure and facade fires. Almost all fire scientists and engineers have had an input in this area. For this reason, I have put two lists of references one that is probably exhaustive (Appendix A) and the other that is related directly to this paper. The latter list is dominated by work done by my group and collaborators in Japan (TUS, Professor Y Ohmiya) and in China (SKLFS, Professor Longhua Hu).

I also point out that I will not include a discussion and relation of the present work with spill plumes where a great difference is that the boundary conditions for the facade flows and flames are better defined especially if mainly under ventilated fires are considered as done here.

It is widely recognized that facade flames and fire spread (see Fig. 1) can create serious hazard in high rise buildings owing to three mechanisms of fire spread:

- Flames ejecting form a window can break the window above allowing ignition in the next floor (leap-frogging)
- Failure of fire stopping between the floor slab and the exterior wall, and
- Heat flux impacts on the internal facade assembly (melting of metals, fire spread within insulation) allowing flames through

In order to design for mitigation of the facade fire spread hazard, one should be able to determine the size of the fire in the enclosure, the ejected facade flame properties (flame height and heat fluxes) and their impact on facade assemblies and building materials. The present paper addresses the enclosure fire and facade flames on an inert wall which are required to a) assess the impact , as for example , on fire resistance and flame spread on possibly flammable facade assemblies and b) provide inputs for the design of a reasonable facade test.

Figure 1 provides also an illustration of the contents of the present paper that consist of the next section on enclosure fires followed by a section on facade flames and then a section on applications of the methodologies, before we present conclusions and remaining challenges for fire safety engineering. In Fig.1 the extent of continuous and intermittent flame ejected from an enclosure fire is indicated where 0.4H is the neutral plane.

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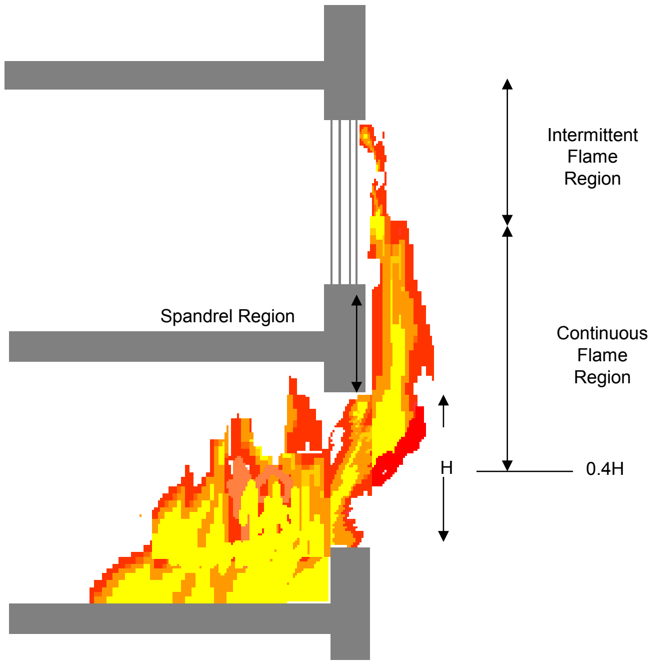

Fig. 1. Enclosure fire and floor to floor external fire spread.

ENCLOSURE FIRES

Mass Pyrolysis Rate

The main thrust of this section is a discussion of the mass pyrolysis rate inside an enclosure having an opening (Fig. 1) as the conditions change from over ventilated (fuel controlled) to under ventilated (oxidizer flow) controlled. For the present purpose, we exclude other interesting phenomena inside the enclosure such as ghost flames, burning oscillations, extinction and re-ignition.

The basic behavior of the mass pyrolysis rate in an enclosure is shown in the sketch of Fig. 2 and in the corresponding data in Fig. 3 [1] for enclosure fires. Both figures show that as ventilation rate (proportional to $A\sqrt{H}$) decreases the mass pyrolysis rate per unit fuel area (A_F) first increases owing to radiation augmentation by the hot gases reaching a maximum and then becomes proportional to the ventilation rate $A\sqrt{H}$ for under ventilated conditions. A significant observation is that the slope of the straight line on the left hand side in Fig. 2 is nearly 0.1, as Kawagoe [2] first found, independent of the fuel type (e.g. its heat of pyrolysis) or the enclosure geometry as long as combustion inside the enclosure can be sustained.

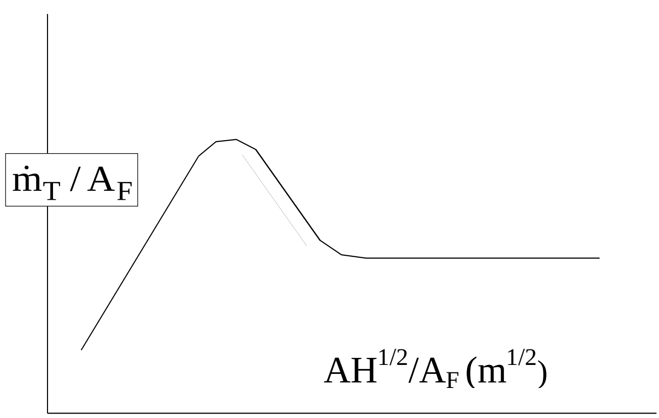

Fig. 2. Mass pyrolysis rate in an enclosure as the ventilation rate varies, both expressed per unit fuel area.

Some recent modeling (Daisuke et al. [3]) of enclosure fires claims to support this result but the physics of why is this so are not clear. *We will come to this matter later but this is clearly is a challenge for fire research.* In addition, the maximum of the pyrolysis rate in Fig. 3 is reached at stoichiometric conditions as Fig. 4 implies because the abscissa is the air inflow for stoichiometric combustion where S is the air to fuel equivalence ratio. We may summarize this section by providing the mass pyrolysis rate for under ventilated conditions as:

$$\dot{m}_T = 0.1A\sqrt{H} \text{ (kg/s) in rectangular enclosures} \qquad (1)$$

Here the area A of the opening is in square meters and the height H of the opening in meters.

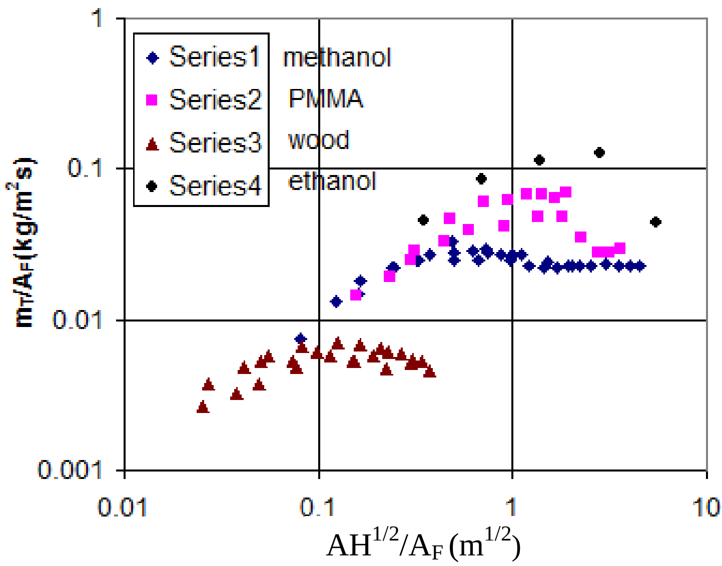

Fig. 3. Experimental data for mass pyrolysis and ventilation in an enclosure for different fuels expressed per unit surface area of the fuel A_F.

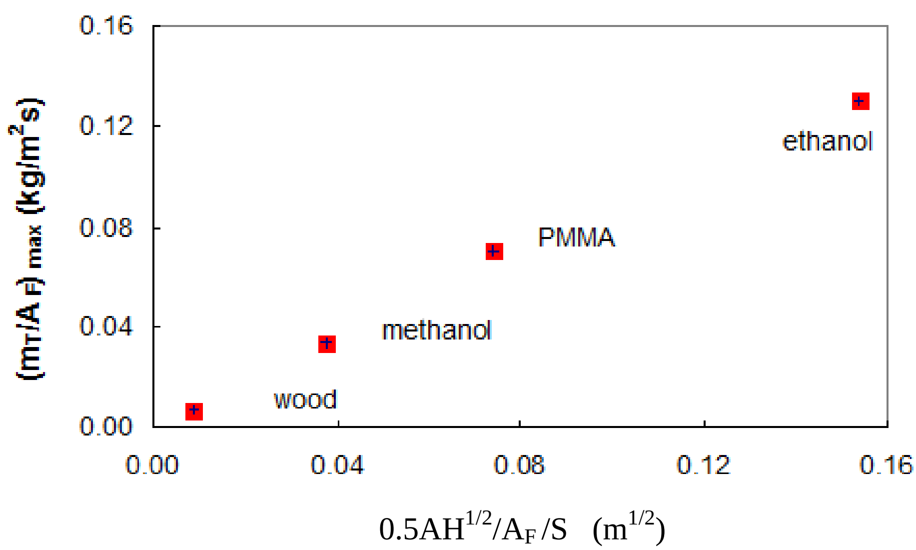

Fig. 4. Maximum pyrolysis rate from Fig. 3 is nearly equal to the stoichiometric requirements for the ventilation rate. The maximum pyrolysis rate is independent of the radiation properties of the fuel which will affect how fast this value is reached from its value at ambient burning.

There is another remarkable discovery related to the mass pyrolysis rate in long corridors (see Fig. 6) as deduced from Fig. 5 for liquid pools [1], namely the mass pyrolysis rate is one quarter of the mass pyrolysis rate in rectangular openings where Eq. 1 applies:

$$\dot{m}_T = 0.025\left(2AH^{1/2}\right) \text{ in corridors} \tag{2}$$

The factor of 2 accounts for the entrainment from both ends of the corridor. *This (slope 0.025 compared to 0.1) is another challenge we and other people try to address.*

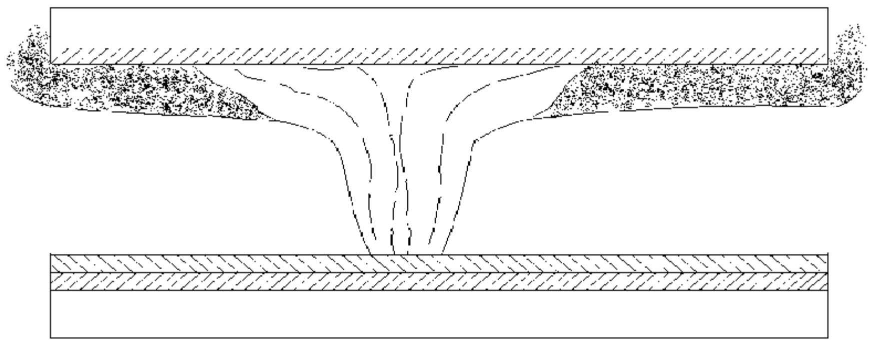

Fig. 5. Flow in a long corridor from a pool fire open at both ends.

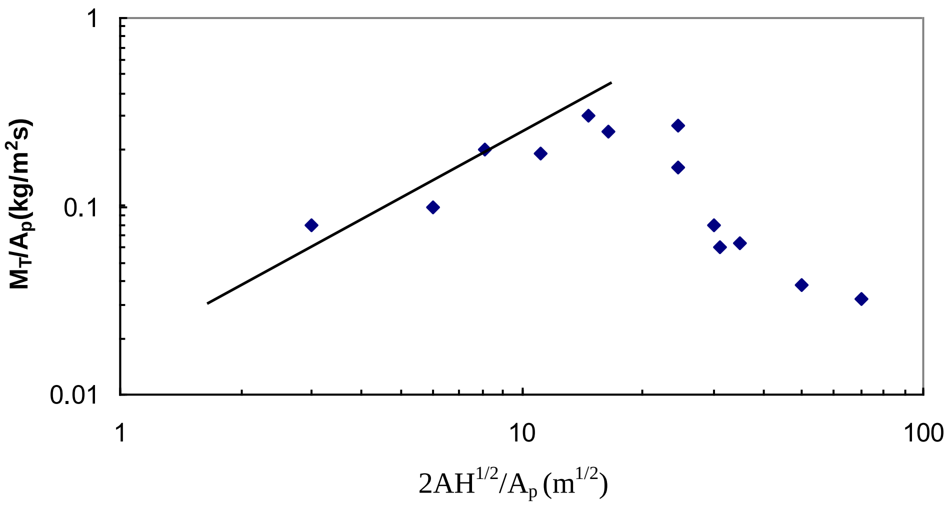

Fig. 6. Correlation of mass pyrolysis rate with the ventilation factor (mass rate of the air inflow) in fully involved corridor fires from under ventilated to over ventilated conditions. *A_p here is the same as A_F namely the fuel surface area.*

We will not discuss here over ventilated fires where an important consideration is the calculation of the heat fluxes to the fuel which consist of radiation from the hot layer, convection and radiation from the flames (e.g. ref [3 – 5]). A simplified methodology based on experiments to estimate these heat fluxes is given by Tofilo et al. [6] also important for the heating and possible breakup of glazing.

Heat Release Rate inside the Enclosure for Under-ventilated Conditions

To address the case of facade flames, one has to be able to calculate the fuel burning outside an enclosure for under ventilated fires which present the major hazard for external fire spread in high rise buildings. First we notice that for under ventilated fires [e.g. 7 – 9] the gas temperatures inside the enclosure away from the opening are nearly uniform. In this case, it has been shown [1, 10] that the air inflow is given by the expression

$$\dot{m}_a = 0.50A\sqrt{H} \text{ (kg/s)} \tag{3}$$

The limitations of this equation have been examined in detail in the Appendix of reference [1] showing a small correction as $\dot{m}_a = 0.50 A_o \sqrt{H_o} - \frac{1}{2}\dot{m}_T$ and a range of applicability for enclosure gas temperatures between 900 to 1200 K. The gas temperatures (not explicitly presented here) inside the enclosure depend on the heat released inside the enclosure, the heat losses to the walls, and the convective and radiative heat losses through the opening [6, 9]. In the following presentation we will use Eq. 3 because it is applicable for the scenarios analyzed.

Subsequent to Eq. 1 it was proposed by several authors [4, 5] that the heat released inside the enclosure is just the heat released by the complete consumption of the oxygen of the incoming air which can be calculated by multiplying the mass air inflow by 3000 kJ/kg , the heat released by the oxygen in air:

$$\dot{Q}_{inside} = 3000 \times 0.50 A\sqrt{H} = 1500 A\sqrt{H} \text{ (kW)} \quad (4)$$

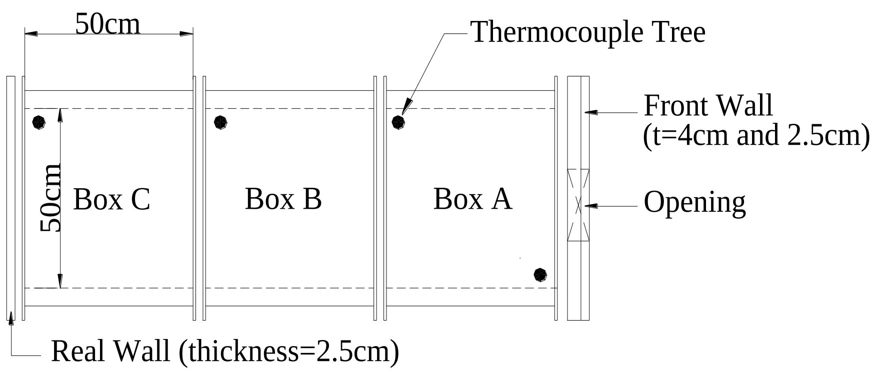

Fig. 7. Modular (box) enclosures used for the facade experiments [6] with a gaseous burner fuel source located at different boxes.

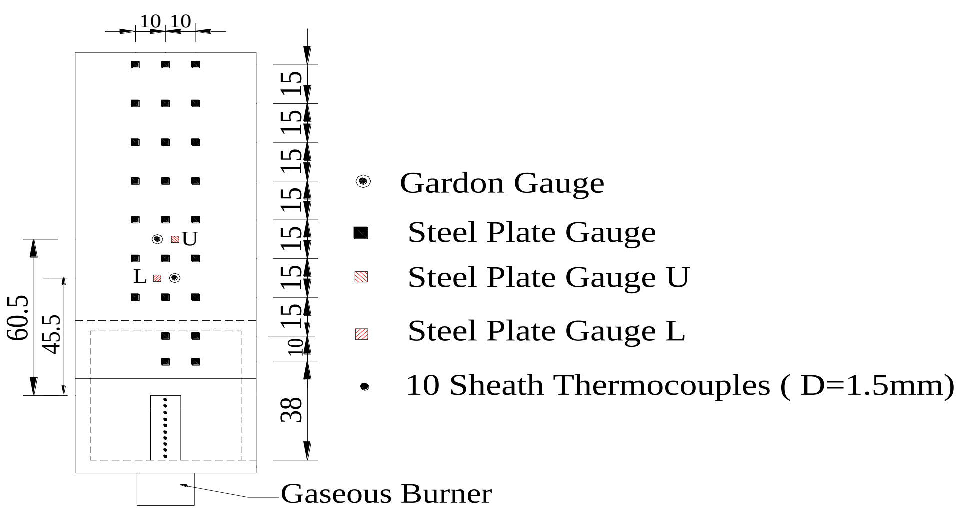

Fig. 8. The facade arrangement with an opening in the front and the instrumentation used in front of the modular enclosure in Fig. 7 [6]

It was shown definitely that this relation is valid in all the experiments by Lee et al. [7, 9] in enclosures using a gaseous burner and a facade well instrumented as shown in Figs 7 and 8. A typical plot of the heat release rate (HRR) measured in a collecting hood is shown in Fig. 9 together with the theoretical HRR of the supplied fuel (straight line) increasing linearly with time from 0 to 50 kW. This figure 9 shows [7, 9] that as the conditions inside the enclosure become under ventilated (in about 8 minutes) and before external burning occurs (at about 13 minute) the HRR inside the enclosure remains constant and is given by Eq. 4 . One can also conclude from these experiments that the same energy is released inside the enclosure even after external burning occurs (at about 13 minutes) because the gas temperatures inside the enclosure [7, 9] do not change after under ventilated conditions establish (in about 8 minutes).

We can now determine the "excess" heat released outside the enclosure as the heat from the complete burning of the fuel minus the heat released inside the enclosure:

$$\dot{Q}_{exc} = \dot{m}_T \Delta H_c - 1500A\sqrt{H} \ \text{(kW)} \qquad (5)$$

Here ΔH_c is the heat of combustion of the pyrolysing material or the gaseous fuel when a gas burner is the source fire. For a pyrolysing material, Eq. 5 together with Eq. 1 provides the following excess HRR;

$$\dot{Q}_{exc} = 0.5\Delta H_c \left(0.2 - 1/S\right)A\sqrt{H} \ \text{(kW)} \qquad (6)$$

Here we have used also the relation between the air to fuel stoichiometric ratio S and the heats of combustion ($S = \Delta H_c / 3000$). *This is another challenge because it proclaims that there cannot be excess HRR and excess pyrolysate (* $\dot{Q}_{exc} / \Delta H_c$ *) if the stoichiometric ratio S <5!*. Having established the relation for the excess HRR, we continue in the next section with the examination of facade flames from enclosures for a gaseous burner fire source where the fuel supply is controlled so that Eq. 5 definitely applies.

FACADE FLAMES

Facade Flames from Under-ventilated Enclosure Fires Under-ventilated conditions exist when the heat release rate from the fuel is larger than $1500A\sqrt{H}$ (kW)as deduced from Eq. 5 and Fig. 9 and also being consistent with the results in Figs. 3 and 4 [7,8,9]. In this case flames will be established outside the enclosure as Fig. 9 also indicates after ignition of the excess pyrolysate occurs at the opening. Until ignition of the external flames occurs the HRR is constant (16.8 kW) as soon as under-ventilated conditions are created inside the enclosure. External burning can also occur at over-ventilated conditions simply when the flames from the source fire are long enough to extend beyond the opening. This situation has been several times confused in the literature to imply under-ventilated fire conditions inside the enclosure.

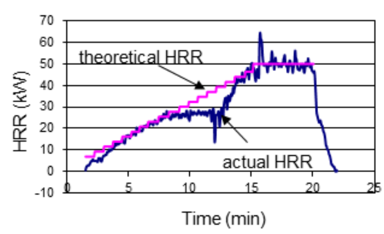

Fig. 9. Theoretical and measured heat release rate history for an experiment having 20 cm by 20 cm opening. The intermediate plateau indicates the heat released inside the enclosure is equal to $1500A\sqrt{H}$ = 26.8 kW.

Turning now to facade flames, we inevitably stumble over the widely used Yokoi method [4, 10] for correlating the gas temperatures of the facade flames. Before we discuss why the Yokoi method should be replaced we note that using the excess pyrolysate (Eq. 5) we were able [7 – 9] to correlate flame heights and heat fluxes to the facade wall using length scales associated with the flow at the exit of the enclosure.

The appropriate length scales derived in Appendices B (where also the Yokoi method is outlined) and C are briefly explained next. The three length scales are

$$\ell_1 = \left(A\sqrt{H}\right)^{2/5} \tag{7a}$$

$$\ell_2 = \left(AH^2\right)^{1/4} \tag{7b}$$

$$\ell_3 \propto (AH^{4/3})^{3/10} \tag{7c}$$

The first length scale is related to the size of the opening required to accommodate the convective flow and the other two length scales are expressing the horizontal extension of the flow with or without flames outside the enclosure owing to the competition of horizontal momentum with the buoyancy. We note that the ratio of these two length scales , $\ell_2 / \ell_3 \propto (H/W)^{1/20}$, varies weakly with the aspect ratio (H/W, height over width) of the window so that ℓ_2 can be retained for correlating the facade flame properties.

Figure 10 shows for example a correlation of the flame height using the length scale ℓ_1 and the non-dimensional excess HRR;

$$\dot{Q}^*_{ex} = \frac{\dot{Q}}{\rho_\infty C_p T_\infty \sqrt{g}\,\ell_1^{5/2}} \tag{8}$$

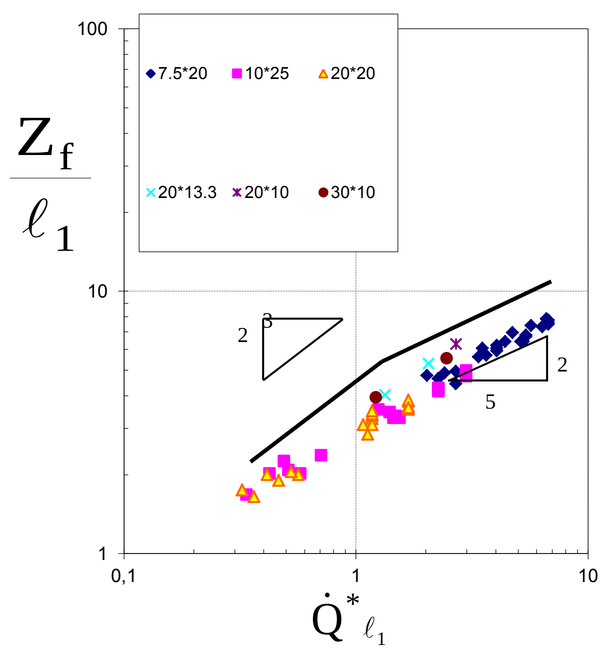

Fig. 10. Flame height correlation using the length scale ℓ_1 (Eq. 7a) and the normalized excess HRR (Eq. 8)

A useful interpretation of this figure is that for $\dot{Q}^*_{ex}$ <1.3 (slope of log-log line 2/3) the flames are two dimensional (like a line plume) and then for $\dot{Q}^*_{ex}$ >1.3 (slope of log-log line 2/5) the flames become three dimensional. The heat flux measurements, see Fig. 11, are also correlated using the same length scales in [7] and in [9] where the heat fluxes on an opposed facade wall are measured and predicted. Heat flux measurements and correlations are essential for the safe design of facade walls. One additional point to make is that the radiation from the facade flames does not depend on the type of fuel in the enclosure because the fuel is preheated to about 800 ˚C before exiting the enclosure thus always producing a lot of soot.

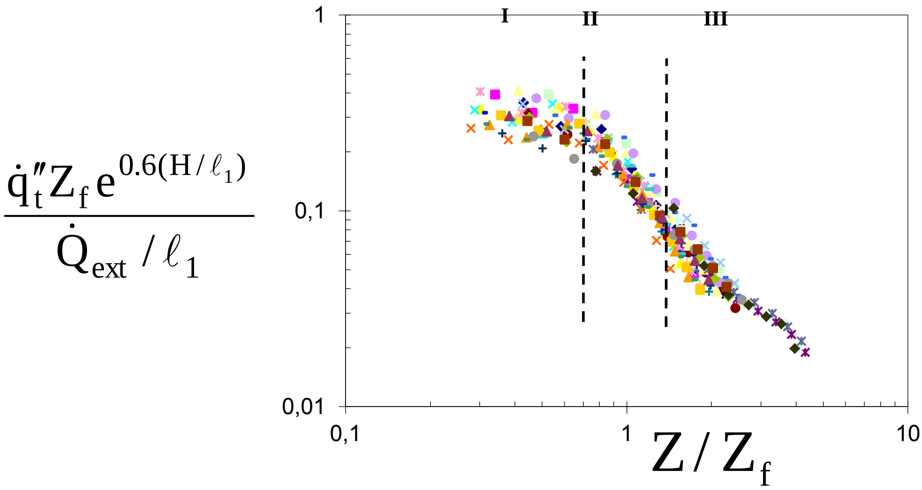

Fig. 11. Heat flux correlation at the center of the facade for all of enclosure geometries and all openings

Sometime after the development of the new length scales [7, 9] we were able to publish [11] a detailed explanation why the Yokoi correlation [10] needs to be replaced. Two modifications were imposed on Yokoi's correlation on the gas temperatures on the facade flow, one replaces his length scale $r_0\ (\propto \sqrt{HW})$ by the new length scale ℓ_1 and the other replaces the local density in the dimensionless temperature by the ambient density. These modifications were justified by analysis and verified (in Figs. 5 and 6 of reference 11) by comparison with Yokoi's experiments of the temperature variation on facades produced from enclosure fires. To my surprise, I discovered, while writing this paper, that Phil Thomas expressed great doubts regarding the Yokoi correlation [12] which are difficult to understand and I have to decided to include them as an Appendix C for the reader.

APPLICATIONS TO OTHER FAÇADE FLAME CONFIGURATIONS

Several applications [12 – 15] of the present results and methodologies have been made in collaboration with the Dr. Longhua Hu team in SKLFS (USTC) and with the Professor Yoshi Ohmiya team at TUS. As an example, we present two new correlations in Figs. 12 and 13 for the flame heights in the case of facade flames with sidewalls and in the case of facade flames from two windows of equal size on the facade wall. These four figures are taken from papers submitted for publication to International Heat and Mass Transfer Journal (sidewalls) and to the Combustion Institute 2014 (two windows).

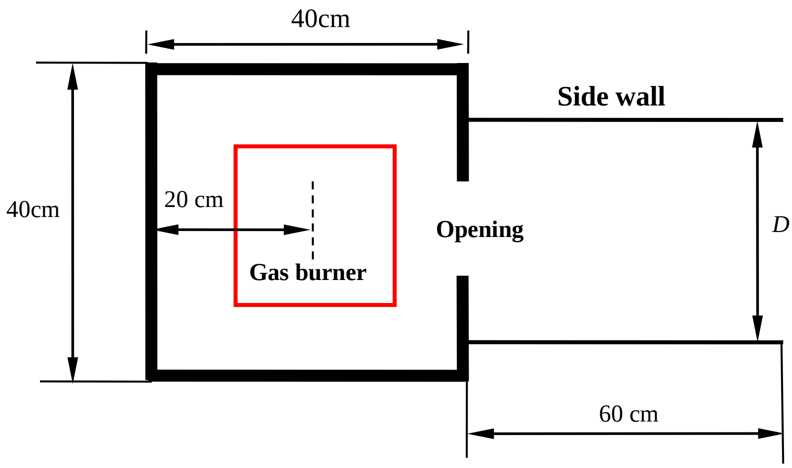

Fig. 12a. Top view of a facade flame experiment for an enclosure with two sidewalls located symmetrically to the opening.

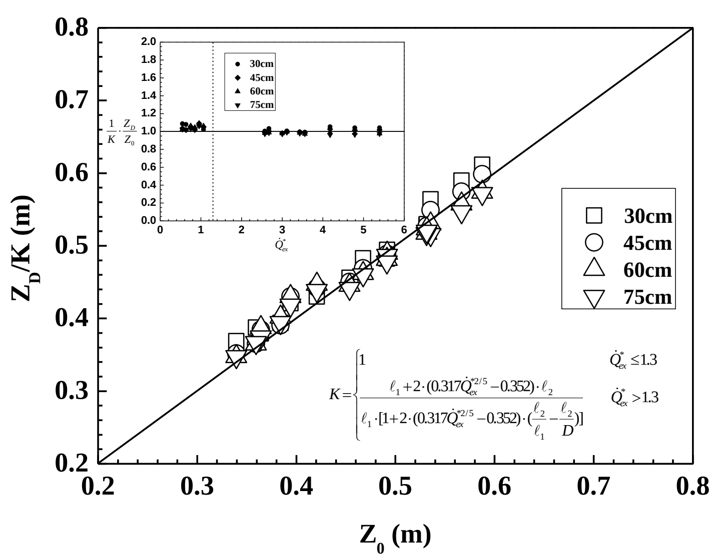

Fig. 12b. Determination of the height of the facade flames at distance D of the sidewalls (Fig. 12a) using the height when the sidewalls are absent Z_0 and the parameter K which depends on the length scales ℓ_1, ℓ_2 (Eqs. 7a and 7b) and the normalized excess HRR (Eq. 8).

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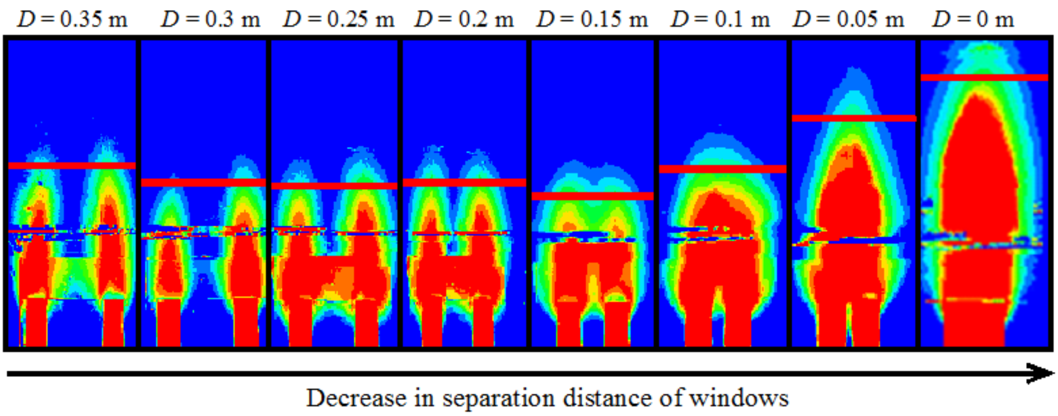

Fig. 13a. Average contour maps of video intensity showing facade flame heights for decreasing separation distance of the window 0.25 m (H) × 0.125 m (W) and heat release rate 164 kW (the horizontal red line for the flame height at 50% intermittency and the horizontal blue lines are background marks).

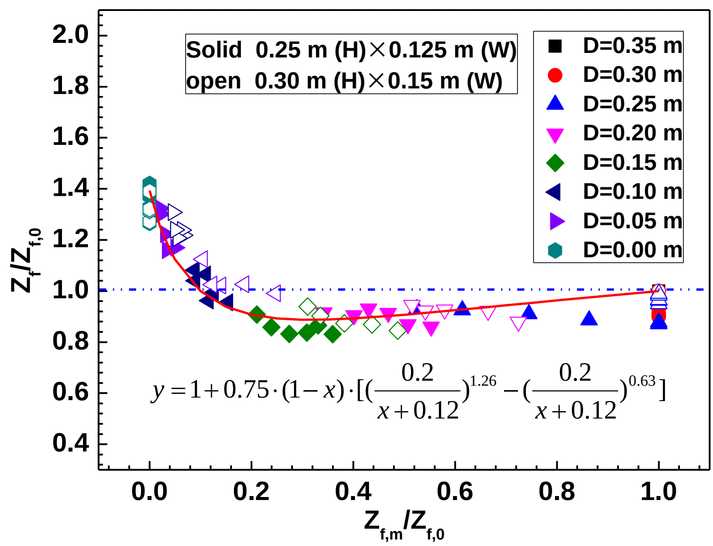

Fig. 13b. Facade flame height Z_f against flame merging point distance $Z_{f,m}$ normalized by the completely non-merging flame height $Z_{f,0}$ where this height is reproducing the data in Fig. 10.

CONCLUDING REMARKS

There are some major challenges for enclosure and facade fires which need explanation and more experiments:

1. The (total) pyrolysis rate for normal enclosures is given by Eq. 1, $\dot{m}_T = 0.1\sqrt{H}$ (kg/s) and for long corridors by Eq. 2, $\dot{m}_T = 0.025\left(2AH^{1/2}\right)$ based on experiments, but there is no explanation for these values. These relations are assumed to be valid for any fuel and any geometry. Daisuke et al. [3] developed a global zone model that corroborates Eq. 1 supported also by his experiments. However, there is not a simple explanation through the equations in [3]. I propose that this behavior is due to radiation blockage near the surface of the fuel owing to pyrolysis gases. This radiation blockage is nearly inversely proportional to the concentration of pyrolysis gases in the enclosure which can be determined by the ratio of the mass pyrolysed to the air inflow:

$$\phi \propto \frac{\dot{q}'' A_F}{\Delta H_p} / \dot{m}_a \qquad (9a)$$

Therefore the mass pyrolysis rate should be

$$\dot{m}_T \propto \frac{\dot{q}'' A_F}{\Delta H_p} / \phi \propto \dot{m}_a \qquad (9b)$$

2. For a pyrolysing material Eq. 5 together with Eq. 1 provides the following excess HRR $\dot{Q}_{exc} = 0.5 \Delta H_c (0.2 - 1/S) A\sqrt{H}$ (kW). *This is another challenge because it proclaims that there cannot be excess HRR and excess pyrolysate* $(\dot{Q}_{exc} / \Delta H_c)$*, if the stoichiometric ratio S <5!*
3. The experiments used in this paper have been in small scale (up to 0.8 m^3 cube) where the flow is turbulent and the conditions are under-ventilated. For these reasons, the results can be applied for larger scales as it was examined in [7] for the work of Oleszkiewicz [16] and recent results of Ohmiya [17].
4. Incorporation of wind effects requires investigation of both the magnitude of the wind and its direction. It is possible based on the present approach to examine when wind may be important by comparing the wind speed with the maximum velocity in the facade fire plume.
5. We have used CFD (mainly FDS) to model the under-ventilated fires including the facade flows but the experience has not yet been successful in predicting the experimental results.

The present results are being used for the rational design and interpretation of a test for facade assemblies that can represent well actual fuel loads and conditions for under-ventilated fires and also be economical.

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APPENDIX A

Extended literature: enclosure and facade fires

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APPENDIX B

Length scales for the convective flow outside the enclosure

We have revised Yokoi's [10] work for the gas temperature distribution along a facade to introduce a length scale that would better collapse the experimental data. Namely, Yokoi [10] proposed to use the square root of the area, $\sqrt{HW}$, of the enclosure opening as an effective length scale for the thermal plume in the facade produced by over-ventilated fires with no combustion occurring outside. Examination of his analysis would show that the appropriate scale should have been $\left(A\sqrt{H}\right)^{2/5}$ instead. Replotting his data in ref. 10, see also our work in [11] verifies this conclusion but because of lack of space we chose not to insert the full explanation and this plot here. Figure B1 illustrates the physical meaning of the scales introduced for the flow issuing at the opening of an enclosure.

Nevertheless, we show in this work how and why this scale is significant for the analysis of flames on facades at under-ventilated conditions. Namely, the convective flow at the exit is defined as:

$$\begin{aligned}\dot{Q}''_{conv} &= \dot{m}_g(\approx \dot{m}_a)C_p\Delta T_g = 0.5A\sqrt{H}C_p\Delta T_g \\ &= \left(\frac{0.5}{\rho_\infty\sqrt{g}}\right)\rho_\infty A\sqrt{Hg}C_p\Delta T_g = 0.13\rho_\infty A\sqrt{Hg}C_p\Delta T_g\end{aligned} \tag{B1}$$

or

$$\left(\frac{\Delta T_g}{T_\infty}\right) = 0.025\frac{\dot{Q}''_{conv}}{\rho_\infty C_p\Delta T_\infty\sqrt{g}\left(A\sqrt{H}\right)} \tag{B2}$$

which indicates that an appropriate length scale is:

$$\ell_1 = \left(A\sqrt{H}\right)^{2/5} \tag{B3}$$

Moreover, an important characteristic (different from other wall fires) of the flows outside the enclosure is that they are ejected horizontally before turning vertically and attaching to the facade. The horizontal length after which the flow becomes vertical can be determined from the momentum and buoyancy at the exit of the enclosure. Specifically, the momentum flux is equal to:

$$M_o \approx \dot{m}_g u \tag{B4}$$

and the buoyancy flux

$$J_o \approx \dot{m}_g\frac{\Delta T_g}{T_\infty}g \tag{B5}$$

where the characteristic exit velocity and the mass flow are:

$$u \propto \sqrt{\frac{\Delta T_g}{T_\infty}gH} \;\; and \;\; \dot{m}_g(=\dot{m}_a) \propto \rho_\infty uA \tag{B6}$$

The characteristic length after which buoyancy dominates is determined by equating the momentum at the origin with the momentum of the developing thermal plume generated by the buoyancy flux after a certain distance:

$$\ell_2 = \frac{(M_o / \rho_\infty)^{3/4}}{(J_o / \rho_\infty)^{1/2}} = \left[AH^2\right]^{1/4} \tag{B7}$$

It is concluded that the length scales $\ell_1 = \left(A\sqrt{H}\right)^{2/5}$ and $\ell_2 = \left(AH^2\right)^{1/4}$ underpin the physics related to the flow at the exit of the enclosure. More specifically, the flow outside the enclosure may be depicted as generated by a rectangular burner having sides ℓ_1 and ℓ_2 (normal to the opening plane) at the level of the neutral plane and providing unburned gas of chemical energy $\dot{Q}_{ex}$.

We chose the length scale ℓ_1 to correlate the flame height and heat fluxes on the facade because we can observe that ℓ_2 is nearly proportional to ℓ_1 varying weakly with aspect ratio of the window, i.e.,

$$\frac{\ell_2}{\ell_1} = \left(\frac{H}{W}\right)^{3/20} \tag{B8}$$

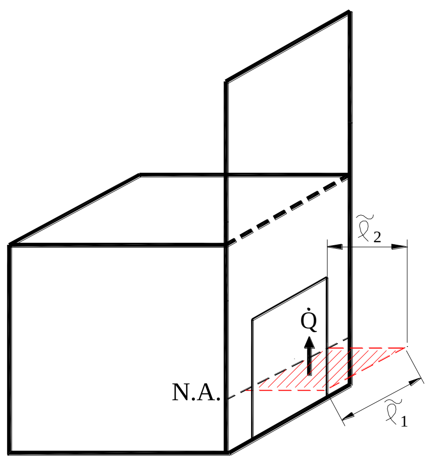

Figure B1 A sketch of the physical meaning of length scales $\tilde{\ell}_1$ and $\tilde{\ell}_2$

APPENDIX C

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.

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

$$M_{ent} \propto \rho_\infty \left(\sqrt{\frac{\Delta T_f}{T_\infty} g\ell_3}\right) \ell_3 \ell_1 \left(\sqrt{\frac{\Delta T_f}{T_\infty} g\ell_3}\right) \tag{C1}$$

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.

$\ell_1 = \left(AH^{1/2}\right)^{2/5}$ is the length representing the exit condition of the enclosure (Appendix B)

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

$$M_0 \approx \rho_g \frac{\Delta T_g}{T_\infty}\left(H - Z_o\right)^2 gW \tag{C2}$$

where: W is the width of the opening

ΔT_g is the temperature rise between gas inside the enclosure and ambient

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. C2) with the vertical momentum (Eq. C1) generated by the buoyancy

$$M_{ent} = \rho_\infty \frac{\Delta T_f}{T_\infty} g{\ell_3}^2 \ell_1 \approx \rho_g \frac{\Delta T_g}{T_\infty}\left(H - Z_o\right)^2 gW = M_0 \tag{C3}$$

Inserting $\ell_1 = (AH^{1/2})^{2/5}$ in Eq. C3 and making arrangement, it gives

$$\ell_3 \propto \left(\frac{\Delta T_g}{\Delta T_f}\right)^{1/2} \left(\frac{\rho_g}{\rho_\infty}\right)^{1/2} \left(1 - \frac{Z_o}{H}\right)\left(AH^{4/3}\right)^{3/10} \tag{C4}$$

In the case of under-ventilated fire condition, Eq. C 4 can be expressed as [1]:

$$\ell_3 \propto \left(\frac{\Delta T_g}{\Delta T_f}\right)^{1/2} \left(\frac{\rho_g}{\rho_\infty}\right)^{1/2} \left(1 - \frac{1}{1 + \left(\frac{\rho_\infty}{\rho_g}\right)^{1/3}}\right)\left(AH^{4/3}\right)^{3/10} \tag{C5}$$

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 °C and 1000°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

$$\ell_3 \propto (AH^{4/3})^{3/10} \tag{C6}$$

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APPENDIX D:

Phil Thomas query of the Yokoi relation [10, 11]

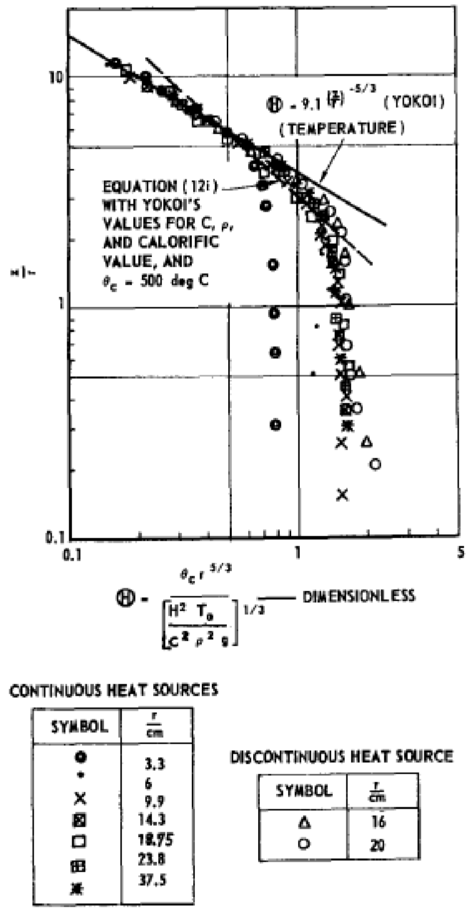

FIG. 9. Correlation for horizontal circular and square heat sources.

with the correlations given in this paper. However, to retain his results in their original form the reverse procedure was adopted; namely, Eq. (12) has in effect been superimposed on Yokoi's results (Fig. 9). The discrepancy in trend between the two sets of data is a result of their different basis. However, the results agree in the region of z/r in the range 2 to 3 corresponding to the heights of the flames for Yokoi's experiments.

Yokoi gives data relating the temperature rise to s, the distance along the trajectory of hot gas emerging from windows, when there is no wall above them, a condition Yokoi refers to as "free space." He also gives data relating s to the corresponding vertical height z which is always less than s.

In comparing these data with corresponding data on flame height the following approximations and assumptions have been made:

(1) $z \doteq s$.

(2) In Eq. (18) m_w is the total rate of burning while in Yokoi's correlation H is the heat passing through the window. It has been assumed that the difference in origin is partially compensated for by using L from the base of the window in a manner analogous to s from the top of the window. The error entailed in this procedure tends to decrease at large values of L/D and z/r.

(3) Flame height and temperature depend on m' and H', respectively, not on m and H.

In the region of z/r and Θ, where the results follow the expected relation for a line source, i.e. $\Theta z/r$ is constant, it would be expected from this last assumption that $n^{\frac{1}{3}}\Theta z/r$ is constant.

Yokoi's data for different values of n do, in fact, follow this law as is seen in Fig. 10. The equation is

$$n^{\frac{1}{3}}\Theta z/r \doteq 1.0,$$

where he uses half the window height for l.

After substituting for n and r the expression becomes

$$z = 1.0(\pi T_0/\rho^2 c^2 g)^{\frac{1}{3}}(H'^{\frac{1}{3}}/\theta_c).$$

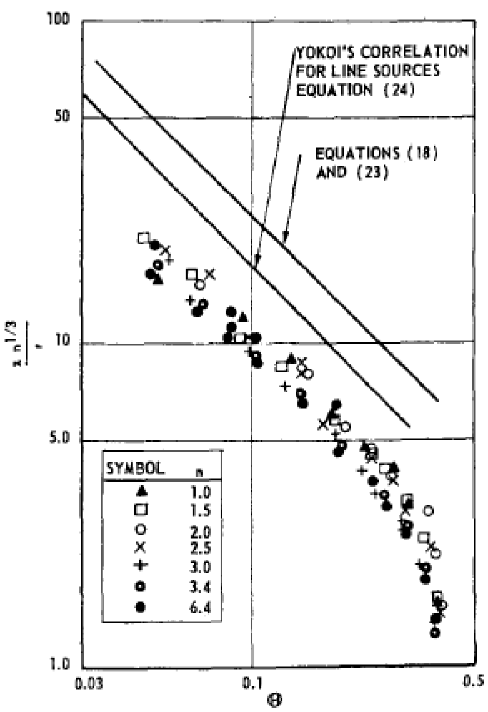

FIG. 10. Yokoi's data replotted as $zn^{1/3}/r$ (hot gases from windows).