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Model of fire spread out on outer building surface

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Abstract. The spread of fire through the façades is one of the quickest routes of spreading flames in buildings.

There are three situations that can lead to the spread of fire though the façades:

a) Fire from outside through hot coals, initialized/set either by a fire in a nearby building or a wooden area in flames,
b) Fire started/set by an element that burns in the front of the façade (garbage container, furniture, etc.),
c) Fire originated in a compartment of the building, which spreads outwards through the windows.

In this paper, I focus only at the last case, which is considered to be the most dangerous and statistically the most frequently occurring.

Fire spread of some type of façades were discussed:

- Glazed façade,
- Double-skin façade,
- Façade with structural barriers,
- Façade with side walls at the opening,
- Façades covered by ETICS (External Thermal Insulation Composite System).

Also information of influence of radiation from compartment fires to adjacent buildings was added.

Key words: fire spread, façade, plume characteristics.

Nomenclature

A_T	–	area of enclosed surface excluding the window [m^2],
A_w	–	area of burn room window/opening [m^2],
b	–	emission coefficient [–],
CEF	–	consistent external flaming,
C_p	–	specific heat [kJ/kg K],
$Đ$	–	equivalent window diameter [m],
D	–	depth of the venting plume [m],
D_c	–	depth of compartment/enclosure [m],
f_{ex}	–	excess fuel factor,
h	–	height of burn room window/opening [m],
hf	–	heat flux,
H	–	height of venting plume [m],
I	–	radiant heat flux density [kW],
k	–	constant in equation 21 [kW/m^2[m^2/kg/s]$^{0.6}$],
l	–	distance along flame axis X [m],
l_f	–	flame length [m],
L	–	total mass of fire load [kg],
$\dot{m}$	–	mass inflow rate of air [kg/s],
n	–	parameter (=w/$\frac{1}{2}$h),
$\dot{Q}$	–	heat release rate [kW],
r	–	stoichiometric ratio,
R	–	rate of burning [kg/min] or [kg/s],
T	–	temperature [$^\circ$C or K],
T_o	–	window/opening temperature [$^\circ$C or K],
ΔT_m	–	centre-line velocity rise above ambient [$^\circ$C],
T_{FDF}	–	average temperature during the fully developed phase [$^\circ$C or K],
$T_{\max}$	–	maximum temperature [$^\circ$C or K],
T_{amb}	–	ambient temperature [$^\circ$C or K],
u	–	wind speed producing during fully developed phase [m/s],
u^*	–	wind based on heat release rate [m/s],
U_m	–	centre line velocity [m/s],
V_{wind}	–	wind velocity [m/s],
w	–	width of the burn room window/opening [m],
W	–	width of the venting plume [m],
W_c	–	width of the compartment/enclosure [m],
WLC	–	window lowering criterion, WLC $\neq$1 or WLC $\neq$1,
X	–	flame axis,
z	–	height above window/opening [m],
Z	–	height above virtual source [m],
α	–	convective heat transfer co-efficient [kW/m^{2}K],
ε	–	flame emissivity,
η	–	parameter (=$A_T/A_w\sqrt{h}$)
φ	–	plume tilt angle [deg],
λ	–	flame thickness [m],
ρ_{amb}	–	ambient density [kg/m^3],
σ	–	Stefan-Boltzman constant ($-5.6699 \cdot 10^{-8}$ W/m^2 K^4),
τ_F	–	free burning duration [min],
Θ	–	dimentional temperature.

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1. Introduction

The façade is the interface between the inside and outside of the building, therefore, it is an area in which converge many factors that facilitate dynamics of fire, such as: unlimited amount of oxygen, the verticality of the surface, the pressure difference between inside and outside of building, the wind. For these reasons, the vertical spread of fire occurs even when the cladding materials of the facades are not combustible.

In this paper a model, of spread of fire on façades is presented in dependence on:

- rate of burning in a room. The ventilation condition within a room directly affects the burning rate of the fuel which in turn affects the severity of a venting fire plume and its shape. The rate of burning in kg/s is given for restricted ventilation condition. When there is sufficient ventilation, the rate of burning can be expressed in terms of fire load and free burning duration. The maximum temperature in a burn compartment is given on the basis of semi-empirical correction,
- projecting flames out of a window after glass is fire-broken. The condition of this phenomenon/these phenomena is given in dependence on temperature condition in burn room,
- as the plume vents from an opening, its shape is affected by the enclosure's ventilation conditions, as well as the window shape. The overall height and width of the venting flames depend on the window aspect ratio, as well as whether; there are horizontal or vertical projections above or beside the window. Flame height, width, temperature along flame centreline will be given,
- the plume often surges out, curling back to make contact with the external wall. An external wall can be also attacked by radiation heat flux. In this case, the way to calculation emissivity is given.

Flame spread behaviours over solid surfaces are the combined results of heat and mass transfer in solid and gas phases, the pyrolysis in solid phase and chemical reaction in gas phase. The common thermal insulation materials used on external walls of buildings are thermoplastic materials (expanded and extruded polystyrene) and thermosetting materials (polyurethane and polyisocyanurate foams). Taking into consideration the flame spread behaviour differences between these two kinds of materials the classic flame spread model over solid surface will be reviewed.

Most research on fire characteristics has concentrated on the "room of fire origin". The amount of data collected in this area of fire research is significant. The effects of fire and smoke spread beyond the room of fire origin (burn room), on the other hand, have not been investigated in the same extend. In this respect, one interesting characteristic of fire is the way it spreads out of openings, such as windows of building. The appearance of flames through windows is caused by the venting of unburned gases from the burn room and their continued combustion beyond the opening where reservoir of fresh air exist. External flaming is a characteristic of fire that have undergone a transition to flashover and entered a ventilation controlled state.

The emerging/venting flames and combustion products, and the risk they pose to external façade of a building are greatest during the fully developed phase of the fire. It is during this phase that temperatures both inside the room of the origin and outside on the façade are at their highest. As a result, secondary fire may initiate, either in the upper levels of the building or adjacent structures via direct flame contact or radiative heat transfer from the venting plume. Factors affecting a fire are primarily the fuel source (type, load and distribution) and ventilating, such as size if openings and rate of burning. These in turn influence the likelihood of external flames. Once the fire extends beyond the compartments, window geometry and presence of other openings, affect the shape of external plume and whether or not re-attachment to the façade occurs, while the environmental conditions influence both swirling of the plume entrainment into it. The external flaming plume can be considered in terms of flame shape (height, width and depth), temperature and velocity distribution within the plume and heat flux received by external or adjacent walls, where all of the above-mentioned factors play an important role.

The need to have a detailed analysis of the venting plume stems from the resent emergence of performance-based codes. In the past, most fire safety design systems and specification were based on empirical relationships. The use of computational fluid dynamic (CFD) and zone models has become an alternative means to predict the effects of a fire, both inside and beyond the room of fire origin. However, before such numerical models can be used in conjunction with performance-based codes and risk assessment models, their prediction need to be validated against results taken during full-scale experiments. While it is possible to use some small-scale fire tests for full scale experiments, the use of full-scale experiments eliminates the difficulties associated with such small-scale correlation.

2. Characteristics of plumes on façades

The fundamental work on plumes was carried out by Yokoi [1] in the 1960s to assess the risks associated with fire spread from window openings in buildings. Yokoi performed both small-scale and full-scale experiments during his investigation of hot upward currents and venting plumes. He noted that the standard glass windows, 3 mm in thickness, mostly cracked when subjected to hot gases at 400°C with dislodgement at 500°C, while wired-glass windows were not expected to crack even when gas temperature reached 600°C. In summary [6, 7], the following semi-empirical equations were developed using Yokoi's data, and expanded by Oleszkiewicz [3] – Fig. 1 and Thomas and Law [2] – Fig. 2.

Trajectory along plum axis (temperature and velocity):

$$\Delta T_m = 24.6\dot{Q}^{2/3}Z^{-5/3}, \tag{1}$$

$$U_m = 1.17\dot{Q}^{1/3}Z^{-1/3}. \tag{2}$$

Re-attachment parameter n:

$$n = w(1/2h) \tag{3}$$

when $n < 3.4$ the plume will be rise close to the wall, but not re-attach. The closer this number gets to 1, the further away from the wall, when $n > 6$, plume strongly deflects towards the wall.

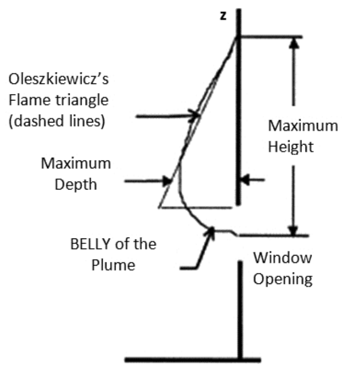


Fig. 1. Schematic side view of the plume after Ref. 3

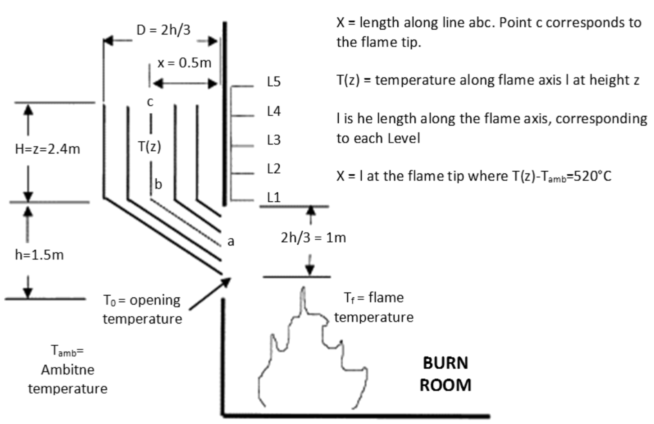


Fig. 2. Schematic representation of the emerging flame (Refs. 2,7) showing flame axis (plume centre line), flame height (H) and width (W), and flame $T(z)$, opening (T_o), ambient (T_{amb}) temperatures

Plume is considered as horizontal jet to predict the size of flames during building fires [4]. This was done with the intension of assessing the use of external structural steel without fire protection. The correlation for flame length assumes a flame tip temperature of 538°C, below which value a significant risk is not posed to exposed steel structures. Adding to the work of Law [2] produce the comprehensive guide to assess the fire safety of external building elements. Correlations were presented for free and restricted burning rates, the dimensions (height, depth and width) of external flames, based on through-draft *(in burn room)* and no-through-draft *(in burn room)* conditions, as well whether or not there is a wall above the opening. In additions, temperature along the flame axis and a model of heat transfer from the flames to the external steel structure were given. This publication was followed by a manual [5].

The venting plume.

Rate of burning. The ventilation conditions within the room directly affect the burning rate of the fuel which in turn affects the severity of a venting fire plum and its shape. Important parameters are the window area, A_w, window height, h, area of the enclosed surface, A_T, excluding the window area, and the ratio of the compartment's depth to width, $\frac{D_c}{W_c}$. The rate of burning in kg/s, derived from experimental studies, for restricted ventilation conditions, is given below [5]:

$$R = 0.1 A_w \sqrt{h}, \tag{4}$$

$$R = [0.18(1 - e^{-0.036\eta})\sqrt{\frac{D_c}{W_c}}\left(A_w\sqrt{h}\right), \tag{5}$$

where

$$\eta = A_T/(A_w\sqrt{h}). \tag{6}$$

When there is sufficient ventilation, the rate of burning can be expressed in terms of the fire load L, and free burning duration, τ_F (the burning duration is about 20 minutes for most types of furniture). The rate of burning is given by:

$$R = L/\tau_F. \tag{7}$$

The fully developed phase of fire can also be linked to the rate of burning. Based of mostly small-scale tests, it has been reported that the fully developed phase of a fire begins when the fuel mass falls to 80% of this original load and ends when approximately 30% of the fuel remains.

External plume shape. As the plume vents from an opening, its shape is affected by the enclosures ventilation conditions as well as the window shape. The plume often surges out of the window, curling back to contact with the external wall some distance above the opening. In general, flames that emerging from narrow windows are expected to project outwards a distance of half of the window height, while flames emerging from wide or square windows can project one and a half times the window's height. Height, H (m), flame width W (m) and depth, D (m) for no-through conditions in enclosure are given as:

$$H = 23.9\left(\frac{1}{u}\right)^{0.43}\left(\frac{R}{\sqrt{A_w}},\right) - h, \tag{8}$$

$$D = 0.605\left(\frac{u^2}{h}\right)^{0.22}(H + h), \tag{9}$$

$$W = w + 0.4D. \tag{10}$$

Empirical approximation for through-draft conditions are summarized as follows:

$$H = 12.8\left(\frac{R}{w}\right)^{2/3} - h, \tag{11}$$

$$D = 2h/3, \tag{12}$$

$$W = w. \tag{13}$$

Centre-line temperature (centre line of venting plume, beginning at the window opening and extending vertically up the external wall).

Temperature along the flame axis $T(z)$:

For no-through conditions:

$$\frac{T(z) - T_{amb}}{T_o - T_{amb}} = 0.019\frac{l A_w{}^{0.5}}{R}. \tag{14}$$

For through-draft conditions:

$$\frac{T(z)-T_{amb}}{T_o-T_{amb}}=0.027\frac{lw}{R}. \tag{15}$$

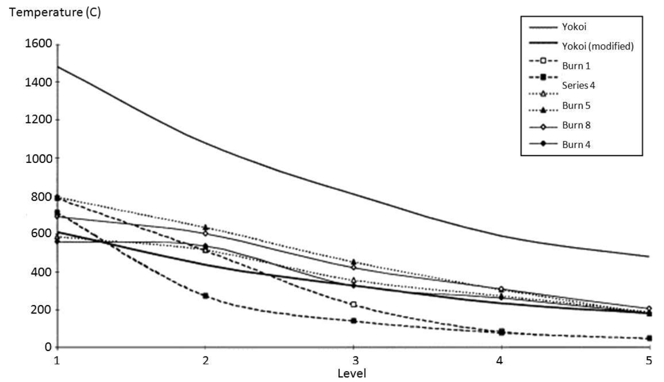


Fig. 3. Measured and calculated center-line temperature distribution for Burns 1-8. Burn 1,2,5,8 (*through-draft conditions*), Burn 3,4,7 *(no-through-draft conditions)* Ref. 7

Temperature in the compartment during the fully developed period *(FDP)* is:

$$T_{FDF}=\frac{6000\left(1-e^{-0.01\eta}\right)}{\sqrt{\eta}}(1-e^{-0.05\phi}), \tag{16}$$

where

$$\phi=L/(A_wA_T)^{0.5}. \tag{17}$$

Convective and radiative heat transfer. Based on flame shape (triangular), the calculated radiant and total heat flux at the flame tip are 520°C above ambient temperature. These equations emissivity, radiant heat flux density and convective heat flux density, are summarized below:

$$\varepsilon(z)=1-\exp(-b\lambda), \tag{18}$$

where emission coefficient $b=0.3m^{-1}$, λ is the flame thickness at height z (and $\lambda=2h/3$ at the top of the opening);

$$I(z)=\varepsilon(z)\sigma[T(z)]^4, \tag{19}$$

$$q\left(z\right)=\alpha[T\left(z\right)-T_{wall}], \tag{20}$$

where α is convective heat transfer coefficient (kW/m^{2}K). The modification is to calculate the convective heat transfer to the external wall above the burn room window from the venting flames, rather than to an exposed steel structure.

$$\alpha=k(R/A_w)^{0.6}, \tag{21}$$

where k is a dimensional factor ($k=0.013$ kW/m^{2}K [m^2/kg/s]$^{0.6}$).

Excess fuel factor

Excess fuel factor was used by [8] to aid their explanation of external flames. They linked the height of the external flames (and radiative heat flux to the façade) to the amount of unburned fuel leaving the compartment. The larger the positive excess fuel factor is, the higher the flame must be. The excess fuel factor f_{ex} is defined by:

$$f_{ex}=1-\dot{m}/rR. \tag{22}$$

For a mass flow rate the following expression is used:

$$\dot{m}=0.5A_wh^{1/2}. \tag{23}$$

Environmental effects. Another important and often neglected aspects, due to its uncontrollability, are the effects of wind speed and direction on externally venting plumes. Cross-winds may skew a venting fire plume, forcing it towards other windows along the same level as the burn room, or diagonally across to upper-level windows. Also, direct (front-on) wind tended to push the plume back against the wall. Sugawa et al. [9] investigated the effect of side winds on plumes venting from openings and developed an expression to determine the flame angle along the trajectory. The flame angle, ϕ, is the angle from the vertical centre of the plume to the horizontal, and is given by:

$$\sin\varphi=V_{wind}/u^*\left(\frac{h}{w}\right)^{1/3}, \tag{24}$$

where u^* is the velocity based on the heat release rate release rate given by

$$u^*=\sqrt[3]{\left(\frac{Qg}{\rho_{amb}T_{amb}C_pw}\right)}. \tag{25}$$

3. Radiation from compartment fire to adjacent building

Radiation from a fire building poses a potential threat to adjacent buildings [9]. If radiation heat flux exceeds the critical ignition heat flux of combustible materials on an external wall of an adjacent buildings, fire could spread from the fire building to its adjacent buildings. Radiation heat flux received by adjacent building is affected by the characteristics of the fire, including the projecting flames out the window and the window size. The maximum radiation heat flux from compartment fire to a target wall occurs during the fully-developed fire phase.

The radiation heat flux is emitted from two radiators – the window radiator and external flame above the window:

$$\dot{q}''_{\exp}=\dot{q}''_w+\dot{q}''_{ef}, \tag{26}$$

where $\dot{q}''_{\exp}$ is the flux heat measured on target wall, W/m^2; $\dot{q}''_w$ is the flux heat from window radiator, W/m^2; $\dot{q}''_{ef}$ is the flux heat from radiator of external flame above the window, W/m^2.

Radiation heat flux coming from the window is given by equation (similar to (19)):

$$\dot{q}''_w=\varepsilon_w\sigma F_{dE-w}T_w^4, \tag{27}$$

where ε_w is emissivity of window radiator (often assume =1); F_{dE-w} configuration factor from window to a point on target wall; T_w is the temperature of window radiator, K.

Two different kinds of temperatures could be used as the temperature of the window radiator: one is maximum room temperature (given by equation (16)) and the other is maximum flame temperature out of the soffit of window. Temperature out of the soffit of window may be lower than room temperature (if little un-burnt fuel flowing out of the opening) or higher (if a lot of un-burnt fuel flowing out of the opening).

If the radiation heat flux from the window is known, the percentage of radiation heat flux coming from external flame above the soffit of the window, f_{qef}, can be calculated:

$$f_{qef} = \frac{\dot{q}_{ef}}{\dot{q}_{\exp}} \times 100\% = \frac{\dot{q}_{\exp} - \dot{q}_w}{\dot{q}_{\exp}} \times 100\%. \qquad (28)$$

Emissivity of the external flame above the soffit of the window depends on flame height. If the flame height is less than 2 m, the temperature of external flame drops quickly as the elevation increases. It is assumed that the temperature of a radiator of the external flame is equal to the average value of the flame tip temperature and the flame temperature out of the soffit of the window. Then the experimental heat flux could be written as:

$$\dot{q}'_{\exp} = \dot{q}'_w + \dot{q}'_{ef} = \varepsilon_w \sigma F_{dE-w} T_w^4 + \varepsilon_{ef} \sigma F_{dE-EF} T_{EF}^4 = \varepsilon_w \dot{q}_w^{\prime B} + \varepsilon_{ef} \dot{q}_{ef}^{\prime B}, \qquad (29)$$

where ε_w is the emissivity of radiator of external flame; F_{dE-EF} configuration factor from radiator of external flame to a point on target wall; T_{EF} is the temperature of external flame radiator, K; $\dot{q}_w^{\prime B}$ is the radiation heat flux emitting from window radiator, W/m^2; $\dot{q}_{ef}^{\prime B}$ is the radiation heat flux emitting from external flame radiator, W/m^2 (assuming external flame radiator is black body). Therefore the emissivity of the external flame radiator could be found by:

$$\varepsilon_{ef} = \frac{\dot{q}'_{\exp} - \varepsilon_w \dot{q}_w^B}{\dot{q}'_{ef}}. \qquad (30)$$

If the flame height is greater than 2 m, the external flame above the soffit of the window is divided into two parts:

- the bottom part is assumed to start from the soffit of window to the point of 2 m below flame tip. Within this range, the flame temperature changes little and could be assumed constant (= temperature of the flame at the point 500 mm above the soffit of the window and 500 mm away the surface of the fire building,
- the upper part from 2 m below the flame tip to the flame tip. Within this range the temperature drops very fast. It is assumed that this temperature is equal to the average value of the flame tip temperature and the flame temperature of the bottom part. To simplify the problem, it is assumed that the external flame has the same thickness in both the upper and bottom part and the same emissivity.

Then the radiation from black body external flame to the target point could be calculated by:

$$\dot{q}_{ef}^B = \sigma F_{dE-BP} T_{BP}^4 + \sigma F_{dE-UP} T_{UP}^4. \qquad (31)$$

It is very important to study the radiation from the compartment to the development of methodology of calculating radiation heat flux from the building, which can be used to calculate the self-separation distance between buildings to prevent fire spread.

4. Fire spread of some type of façades

4.1. Glazed façade. An architectural design incorporating glass panels are used extensively in modern high-rise building. Glass is non-combustible material (class A1 reaction to fire) so is not contributed in combustion but is contributed in fire. Glass facade is the weakest part in the building envelope and can be broken easily when exposed to a big fire. This can create an inlet for hot gases into the room from the outside, resulting in the fire in the compartment spreading to other floors or rooms. Glazed façade can be attacked by flame emerging from burn room in the way described in previous points of this paper. The temperature gradient between the exposed and shaded region of the glass panel is thought to be the main cause for glass breaking when subjected the fire.

The other cause for glass breaking is the temperature gradient between exposed and ambient sides [11] – Fig. 4. There are a number of cases of glass façades:

- with frames and with or without o thermal movement restriction,
- without frames and with or without o thermal movement restriction.

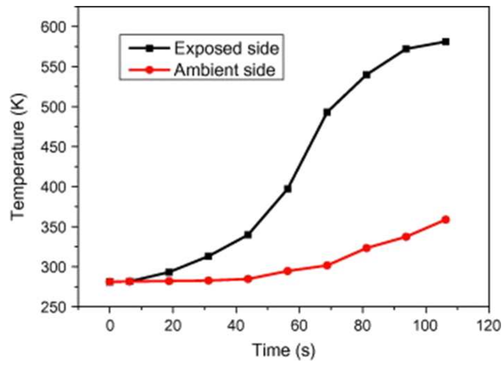


Fig. 4. Glass temperature rising history upon the exposed and ambient sides after Ref. 11

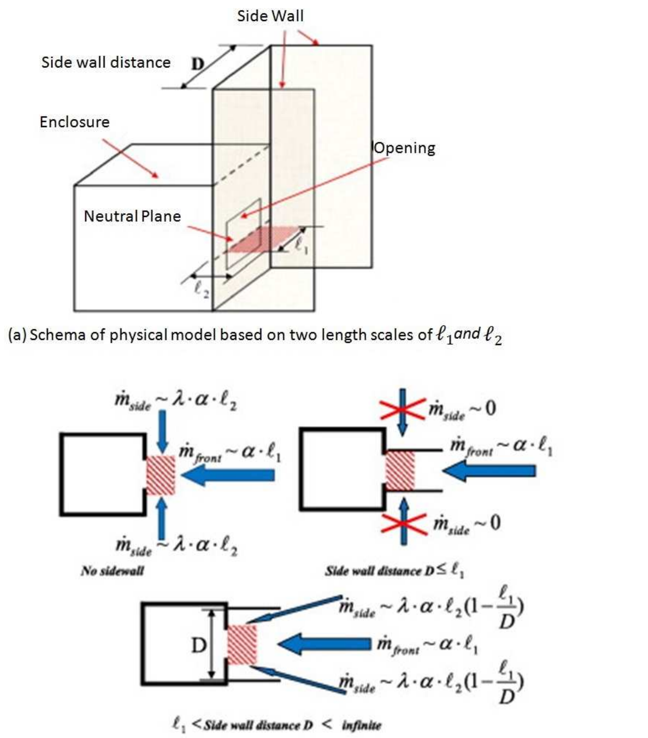
A frame can influences on glass breaking (temperature gradient between the exposed and shaded region). In some cases the frame imposes no restraint on the glass since the maximum expansion is less than the normal gap between the frame and the pane. Some cases are in differently constrained forms. Glass panes are supported by two opposite edges or four edges. If one side is constraint, the side may not have any displacement in x, y or z direction. The studies on glass braking usually employs dynamic response model or thermal stress model (but this is out of interest of this paper).

4.2. Double-skin façade. Double-skin facades (DSF) have become very popular in recently years. A double skin facade of a building consists of inner and outer skin. It can offer several advantages compared with a traditional glazed facade (reduce the acoustic impact on a building, reduce solar heat gain, reduce heat load for artificial lighting and conditioning – reduce the consumption of energy). However, this kind of structure might increase the fire risk, if the inner glass of DSF is broken during fire, smoke and flame moving out to the cavity may spread to the adjacent levels. The depth of the cavity is identified as one of the key parameters in fire spreading in building with DSF. Smoke movement leading to glass damages has been studied by full scale by Chow and Hung [12], surface temperature and heat flux received were recorded. However, these data are not enough for analysing the smoke flow pattern in DSF. So, Junmei et al. [13] study smoke movement inside the cavity using numerical method. The CFD code FDS (Fire Dynamic Simulator) was used. The transient conservation equations of mass, momentum, energy and species for low-speed motion of a gas are solved numerically. Subgrid turbulence, combustion reaction (using mixture fraction model), heat transfer to solid surfaces and convection within the fluid are taken into account. Radiative transport equation for absorbing, emitting and scattering medium is also solved. Higher temperature differences between outer and inner skin were found when cavity depth was small. When the cavity depth being large, lower curtain wall surface temperature could be found, due to more cool air being entrained by hot smoke in the cavity. For the narrow cavity inner surface temperature was found higher. It was found that a deeper cavity might be better safety, the outer glass would be broken rapidly for narrow cavity. If inner glass panel might be broken before the outer skin, might lead to fire spread to adjacent upper levels.

4.3. Façade with structural barriers. Yokoi's [1] experimental work revealed that 0.74 m horizontal projection perpendicular to the wall above the window prevented the glass window above the projection from breaking. These findings led to building code changes in Japan, requiring some structures to have horizontal projection equivalent to today's balconies. Without the presence of a balcony, fire projecting from a window tends to travel vertically, unobstructed along the wall. However, the presence of the balcony can deflect a flame outward, away from the wall, thus impending the vertical fire spread and reducing radiation to the floors above. The key to reducing vertical fire spread is in preventative measures such as window and balcony geometry. Oleszkiewicz [3] experimentally investigated the effect of window geometry in burn room. Results showed that a very low height and wide window provided the most flame exposure to the wall above, while a relatively square window provided the least flame exposure. The hot gases passing through the low, wide opening had lower velocities and the flame attached to the wall more easily than a tall, narrow opening. Also the effect of vertical and horizontal projection on vertical fire spread was examined. In one test, a horizontal projection was placed directly over a window opening. Another test placed vertical projection along both sides of the window. The horizontal projection decreased the heat flux to the wall above the opening by 90%, whereas the vertical projection increased the heat flux by 50%. In the mid-1990s Galea, Berhane and Hofman used a commercial code (FLOW3D) to model the effects of window geometry and horizontal projections on vertical flame spread [17]. The results agreed with Oleszkiewicz and showed that a wide window caused the flame to attach to the wall above. Mammoser and Battaglia [16] used previous experimental work as a basis for comparison with the numerical simulation. It seems reasonable that numerical simulation can be useful in analysing building fires and have the flexibility to change parameters without the expense associated with experiments. At the outset, numerical simulations were conducted for full-scale building fire. However, to adequately resolve the flow field in the full-scale numerical simulations required the excessive computational time. The next step was to explore the use of scale modelling for the computational investigations. The primary objective of this study was to computationally investigate fires ejecting from an opening of a multi-story building to determine how balcony depth affects the flow of hot gases. The secondary objective is to find an optimal balcony geometry (depth and balustrade/separation wall configuration) to best impede the vertical spread of fires. The paper is laid out as follows. First, the physics, combustion and radiation models used in the numerical code will be briefly discussed. The geometry, relevant physics and scaling laws for the simulation will be addressed. Results for a simply balcony geometry were presented. Finally, more complex balcony geometries are presented with results and discussion. Simulation methodology is conducted using fire dynamics simulator (FDS). The numerical simulations show the same general trends as the experiments by Suzuki et al. [18]. It was determined that the use of scale modelling in the simulation was advantageous in that higher grid resolution could be obtained without the added expense of CPD hours. The scaling laws were tested by comparing numerical simulation for full scale fire. A 48 kW fire at the 1/7 scale was shown to be approximately equivalent to a 6.22 MW full-scale fire, which is realistic for a similar size occupant dwelling with typical furnishing. The numerical simulations were then compared to scale experiments by Suzuki for varying balcony depths 0 to 20 cm (0–1.4 m full scale). The gas temperatures at the first and second floors above the fire floor were similar to that from Suzuki. In both experiments and these simulations, an increased balcony depth projects hot gas away from the facade of the building, reducing the heat flux to the surface and thus delaying vertical fire spread. Finally, keeping the balcony depth =17.5 cm, the effect of balcony geometry was investigated. Four different types of balconies were identified and classified. The balcony types contained different balustrade and separation wall configurations. Changing the geometry of the balcony had a measurably effect on the vertical movement of smoke and gas. A rectangular balcony, with open, non-combustible balustrades and open separation walls, provided the most protection from vertical fire spread. A balcony with solid balustrades and separation wall was shown to trap hot gases at floors above the fire floor and increase the rate of vertical fire spread.

Another studies on effect of balcony on vertical spread of window spill plume along exterior façade are given in other papers [14, 15].

4.4. Façade with side walls at the opening. Another kind of entrainment constraint boundary effect, which is due to the presence of side walls beside the window, also exists in practice. A narrow channel is formed by two parallel side walls constructed vertically beside the window, and will influence the window-ejected flame behaviour. The window ejected flame was observed to be remarkably high in the narrow vertical channel formed by two parallel side walls. The presence of the side walls and their separation distance will strongly block the entrainment of fresh air from side – Fig. 5.



(a) Schema of physical model based on two length scales of ℓ_1 and ℓ_2

(b) Entrainment of air at the three sides of the façade flame with and without side walls

Fig. 5. Physical model to characterize the side wall constraint effect on entrainment of the facade flame ("axisymmetric fire like") outside the opening in Ref. 20

It was found [19–21] that the dimensionless excess heat release and the distance of side walls are two major factors under side wall constrains.

Heat release rate inside burn room is given as:

$$\dot{Q}_{inside} = 1500 A_w \sqrt{h} \tag{32}$$

when the theoretical heat release rate from the fuel supplied in the enclosure exceeds the critical value in this equation. The excess fuel burns outside the enclosure creating the façade flames.

$$\dot{Q}_{ex} = \dot{Q} - \dot{Q}_{inside}, \tag{33}$$

where $\dot{Q}$ is a total heat release rate of fuel, $\dot{Q}_{inside}$ heat release rate inside burn room, $\dot{Q}_{ex}$ heat release rate of fuel unburned in burn room.

The mean flame height depends on:

$$\frac{H_f - H_n}{l_1} = f\left(\dot{Q}_{ex}\right) = f\left(\frac{\dot{Q}_{ex}}{\rho_{amb} C_p T_{amb} \sqrt{g \ell_1^{5/2}}}\right), \tag{34}$$

where H_f is the mean flame height, H_n is the location of the neutral plane, ρ_{amb} is air density, C_p is specific heat of air at constant pressure, T_{amb} is an ambient temperature, $\ell_1 = (A_w \sqrt{h})^{2/5}$ it is the characteristic length scale describing the opening size.

These equations are valid on plain façades. For side walls a global dimensionless parameter K is introduced to describe mean flame height in this conditions:

$$\frac{H_D}{\ell_1} = K \frac{H_o}{\ell_2}, \tag{35}$$

where ℓ_2 describes the competition of momentum and the buoyancy flux at the opening for the case of under ventilated fire conditions=$(A_w h^2)^{1/4}$, Z_o mean flame height without side walls, H_D mean flame height with side wall distance of D.

It is known that the flame ejecting behaviour is closely related to air entrainment from surrounding. When the hot unburned fuel is ejected from the opening and move upwards, it does not come to flames until the mixing of fresh air is sufficient to support combustion, which means that the flame height has a negative correlation with the entrainment of fresh air. For the open space without side walls, entrainment occurs from three sides of the rectangular of length ℓ_1 and ℓ_2 and the relative entrainment length scale is supposed to be $\ell_1 + 2\lambda\ell_2$. For another extreme conditions that the distance of side walls is ℓ_1 where the entrainment from side is fully constrained, the total entrainment amount takes only o length scale of ℓ_1. Here λ is introduced as a coefficient to describe the difference of entrainment strength from side with that from front.

Here when a distance of side walls ranges from ℓ_1 to infinity (equals to open space), the parameter K is valued from $\frac{\ell_1}{\ell_1 + 2\lambda\ell_2}$ to 1.

After modification (and taking $\lambda = 0.2$) the parameter K is given by:

$$K = 1 \quad \text{when} \quad \dot{Q}_{ex} \leq 1.3 \tag{36}$$

or

$$K = \frac{\ell_1 + 0.4\ell_2}{\ell_1[1 + 0.4\left(\frac{\ell_1}{\ell_2} - \frac{\ell_2}{D}\right)]} \quad \text{when} \quad \dot{Q}_{ex} > 1.3. \tag{37}$$

It was stated during experiments that for a small dimensionless excess heat release $\dot{Q}_{ex}$, the mean flame height has little dependence on a distance of side walls. For a relative larger flame ($\dot{Q}_{ex} > 1.3$) with the narrow down of the distance of side walls, the influence becomes more and more crucial and the mean flame height is much higher than of free condition. A global parameter K is founded to predict the mean flame height of spill flames under different side wall constrains [20].

4.5. Façades covered by ETICS. Flame spread behaviors over solid surfaces are the combined results of the heat and mass transfer in solid and gas phases, the pyrolysis in solid phase and the chemical reaction in gas phase. In real fire scenario, flame spread behaviors are affected by lots of factors, such as the ambient flow velocity, the oxygen concentration, the pressure, the radiation intensity, and so on [22]. The controlling mechanisms of flame spread behavior are different in different external conditions. The flame spread models can be classified according to their features:

- the heat transfer models and chemical kinetic models, according to in which model the chemical kinetic reaction are considered (the chemical kinetic process can be ignored in the heat transfer model),
- the opposed flow flame models and the con-current flame spread models, based on whether the direction of flame spread is the same with the ambient flow direction,
- the horizontal flame spread model, the upward flame spread models and the downwards flame spread models, based on the direction of flame spread relative to the gravity direction.

The common thermal insulation materials in buildings are thermoplastic materials such as extruded polystyrene (XPS) and the expanded polystyrene (EPS). These materials would melt, and then the melted materials drop and flow. These behaviors caused the differences of flame spread behaviors over the thermoplastic materials from the common thermosetting material such as polyurethane foams (PUR) and polyisocyanurate foams (PIR). So classic flame spread models over solid surface can be reviewed from the aspects of thermoplastics materials and thermosetting materials.

Typical flame spread models over thermosetting materials are;

- the deRis model [23], Fig. 6,
- the Quintiere model [24], Fig. 7.

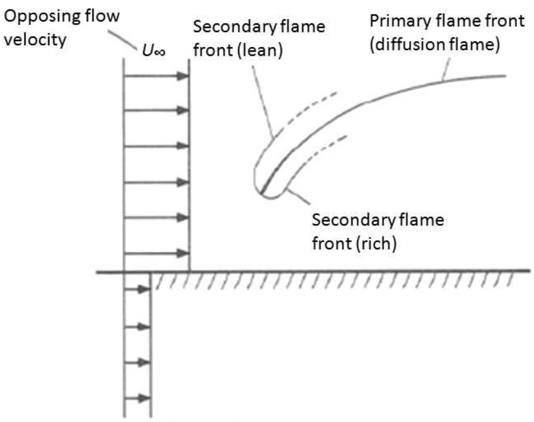


Fig. 6. The flame spread model by deRis (Ref. 23)

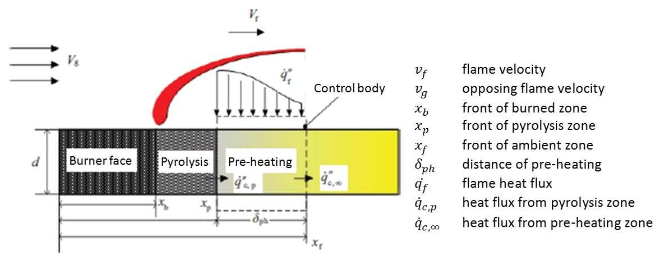
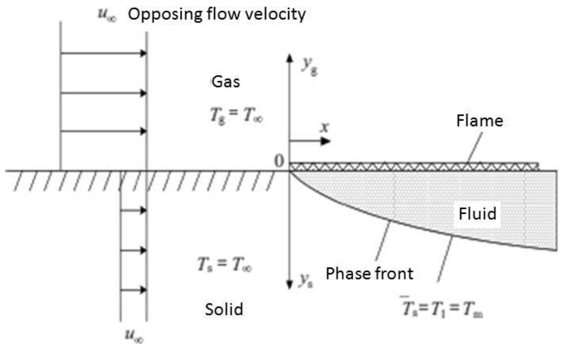


Fig. 7. The flame spread model of Quintere (Ref. 24)

Delichatsios [25] established a flame spread model over thermoplastic material in opposed flow, Fig. 8.



$T_g = T_\infty$ temperature of gas equals ambient temperature

$T_s = T_\infty$ temperature of solid equals ambient temperature

$T_s = T_l = T_\infty$ temperature of solid equals temperature outside phase front equals ambient temperature

Fig. 8. Flame spread model over thermoplastic material in opposed flow (Ref. 25)

These models have well characterized the controlling mechanisms, such as chemical reaction rate, heat loss etc. of flame spread over solid surface as well as over the thermal insulation materials under different conditions. There are not applicable to understand flame spread behavior along façade. These models are address to one component materials that's why they are not applicable for composite products such as ETICS. ETICS (External Thermal Insulation Composite System) consisting of following components being applied directly into façade:

- adhesive,
- insulation material,
- anchors (if required),
- base coat,
- reinforcement (glass fibre mesh),
- finishing coat (top coat with system primer and/or paint coating).

Such a work (models) is needed to be quantified in the future work.

5. Summary of observations from case studies

The Fire Protection Research Foundation initiated a project to develop the technical basis for fire mitigation strategies for fires involving exterior wall systems with combustible components. The first phase of this project is technical report [26] with typical fire scenarios, test methods, criteria as well other approval/regulatory requirements for these systems and also identification of knowledge gaps and recommended fire scenarios and testing approach for possible future work. Just below, in extenso, are conclusions of this report:

- Although exterior wall fires are low frequently events, the resulting consequences in terms of extent of fire spread and property loss can be potentially very high,

- For the most incidents reviewed the impact on life safety in terms of deaths has been relatively low with the main impacts being due to smoke exposure rather than direct flame or heat exposure. However a large number of occupants are usually displaced for significant periods after the fire incident,
- Fire incidents appear to predominantly have occurred in countries with poor (or no) regulatory controls on combustible exterior walls at the time or where construction has not been accordance with regulatory controls,
- Internal fires which spread to exterior walls are the most common fire start scenario for the incidents reviewed,
- Falling burning debris can be significant hazard relating to these fires and causes downward fire spread,
- Re-entrant corners and channels that forms "chimneys" has led to more extensive flame spread than flat walls. The effect of balconies forming partial vertical "channels" should be further investigated,
- Combustible exterior wall systems may present an increased fire hazard during installation and construction prior to complete finishing and protection of the system. The 2009 CCTV Tower Fire and 2010 Shanghai Fire in China are examples of large fire occurring during construction.

The other initiative was an international seminar for fire safety of façades which took place in November 2013 in Paris. During this seminar was presented new method of fire performance testing of external wall cladding systems (previously presented in Technical Report [27]. In this Technical Report proposal of large-scale methodology for non-bearing external wall cladding systems, with or without insulation, applied for outer surface of a building. This test methodology is used to determine spread of flame and contribution to fire.; the fire exposure is representative of a fully-developed (post- flashover) fire in a room, venting through an opening such as a window aperture, or an external fire source (such as waste storage container etc.), that exposes the cladding to the effects of external flames. In order to consider different regulatory requirements this methodology comprises two different testing scenarios.

The following parameters are to be assessed:

- Fire spread (inside and outside of the external wall cladding system),
- Maximum dimensions of flame spread,
- Temperature/time characteristics,
- Continuous smouldering and glowing combustion,
- Mechanical performance including, but not exclusive to, falling of burning droplets/particles, collapse of cladding system,
- Details of visual performance photographically and continuous video recorded and timed observations recorded during tests,
- Areas damaged by fire in all layers assessed by a post-test analysis.

This test specification provides two exposure types (two scenarios)

- Type 1 – the fire source is a nominal 30 kg wood crib and the minimum test height of the test specimen is 5.5 m,
- Type 2 – the fire source is a nominal 382.5 kg wood crib and the minimum test height of the test specimen is 9 m.

6. Conclusions

1. Internal fires which spread to exterior walls are the most common fire start scenario for spread of fires on facades,
2. Spread of fire can be estimated using three ways:
    - semi-empirical approach,
    - computational study,
    - experiments.
3. The basis of a semi-empirical approach are tests in small-scale. The results are then extended on other scales and conditions: the semi-empirical formulas are formed. These models are useful for facades consisting of noncombustible materials. Till now models of fire spreading over combustible façades have not existed.
4. A computational study is useful for estimating movement of products of fire along facades in order to estimate a building façade geometry (glazed façade, double-skin façade, façade with structural barriers, façade with side walls at the opening, fire-stopping),
5. Both semi-empirical approach and computational study should be validated by full-scale tests,
6. A lot of standard tests for estimating spread of fire on facades exists. There is a need to introduce one common method of testing. EOTA proposal is supposed to be a solution,
7. A well-though-out fire safety strategy and façade design are critical. Below attached content is proposed as solution:
    a) Work origin
    Fire statistics – fires of façades and roofs
    Requirements of building code rules concerning fire spread
    Assessment of properties of building's materials and products concerning fire spread,
    b) Scenario of fire spread over façades and roofs.
    c) Physico-mathematical model of fire spread over façades and roofs.
    d) Testing of fire spread over roofs:
        - according to ENV 1187 meth. 1-3,
        - according to SBR (Single Burning Roof).
    e) Testing of fire spread over façades:
        - intermediate scale,
        - full scale.
    f) EU-Agreed method of testing fire spread.
    g) Properties of building products/materials and end-use parameters influencing fire spread. Extended application of results of testing.
    h) Requirements of building code rules versus conclusion of this work. Proposals of changing.

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