WILL IT SUPPORT A SELF-PROPAGATING FIRE?

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Introduction

Regulators need to know *whether (or not)* a fire resistive material *will ignite* rather than how long it takes to ignite when subjected to a given heat flux. The former (i.e. go/no go) question can be addressed as a steady state process, and thus is easier to answer both experimentally and theoretically. In a similar manner regulators need to know *whether (or not)* a fire resistive material can *support a self-propagating* fire rather than how fast the fire might propagate when subjected to a given exposure fire. Once again the former (i.e. go/no go) question is easier to answer both experimentally and theoretically because it can be addressed as a steady state process.

Here we develop a mathematical model for whether or not a fire resistive material can support a self-propagating fire in the parallel panel geometry shown in Figure 3. It is a simple geometry. It subjects the test material to its own flame heat flux. It is a large enough to be realistic, yet uses a minimum of test material. The test is regarded as conservative by FM Global engineers.

Model Assumptions

1. The chemical heat release rate per unit flame volume is a constant

$$\dot{q}'''_{ch} = const = 2000\ kW/m^3 \tag{1}$$

   Several experimental studies have shown that the flame volume to be directly proportional to the chemical heat release rate of the fire[1,2].

2. The flame volume, $V_f = l_f wd$, is a rectangular parallelepiped having width, w, panel separation, d, and flame height, ℓ_f, which is given by

$$\ell_f = \frac{V_f}{wd} = \frac{\dot{Q}_{ch}}{\dot{q}'''_{ch} wd} \tag{2}$$

   where $\dot{Q}_{ch}$ is the total chemical heat release rate of the fire. See Figure 3.

3. The area of the flame in contact with the sidewalls, A_{sw}, and total exterior area of the flame, A_f, are respectively

$$\begin{aligned} A_{sw} &= \mathbf{2}\ell_f w \\ A_f &= \mathbf{2}\ell_f w + \mathbf{2}\ell_f d + \mathbf{2}wd \end{aligned} \tag{3}$$

4. The fraction of chemical heat release returning to the side walls

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[1] Orloff, L. and de Ris, J., "Froude Modeling of Pool Fires," *Nineteenth Symposium (International) on Combustion*, The Combustion Institute, pp. 885-895, (1982)

[2] de Ris, J., "Fire Radiation – A Review," *Seventeenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, p. 1003, (1979).

$$\frac{\dot{Q}_{sw}}{\dot{Q}_{ch}} = \frac{A_{sw}}{A_f}\chi \tag{4}$$

is proportional to the fraction of the total flame area that is in contact with the sidewalls multiplied by a combined blockage and flame sootiness factor, χ to be discussed later. This proportionality with flame area is appropriate in the case of radiative heat transfer, which tends to leave equally in all directions. In the case of convective heat transfer one notes that the large convective heat transfer leaving the top of the flame is roughly compensated for by zero convective heat transfer along the side boundary where air enters the flames.

5. The flame heat flux imposed on the sidewalls, $\dot{q}''_f$, is equal to the total heat transfer to the walls divided by the area of the flame in contact with the walls.

$$\dot{q}''_f = \dot{Q}_{sw} / A_{sw} \tag{5}$$

6. The fuel mass flux leaving the sidewalls, is equal to the flame heat flux minus the surface heat loss by reradiation ("critical heat flux") all divided by the fuel heat of vaporization.

$$\dot{m}'' = \left(\dot{q}''_f - \dot{q}''_{loss}\right) / L \tag{6}$$

The present quasi-steady model does not consider transient effects.

7. Conservation of energy. That is, the overall chemical heat release rate

$$\dot{Q}_{ch} = \dot{Q}_e + \Delta H_{ch} A_{sw} \dot{m}'' \tag{7}$$

is equal to the heats release rate of the exposure fire, $\dot{Q}_e$ plus the heat release rate of the burning sidewalls.

Non-Dimensionalization

These seven assumptions lead to a simple algebraic equation for the overall chemical heat release rate, $\dot{Q}_{ch}$, for a given exposure fire size, $\dot{Q}_e$. To fully examine all possible outcomes, it is best to put the model into dimensionless form.

First, we need to arrive at a single governing equation. Substitute the fuel mass flux (assumption 6), into the conservation of energy (assumption 7) to obtain

$$\dot{Q}_{ch} = \dot{Q}_e + \left(\dot{q}''_f - \dot{q}''_{loss}\right) A_{sw} \Delta H_{ch} / L . \tag{8}$$

Next, using assumptions 4 and 5, substitute for the flame heat flux to arrive at the single governing equation

$$\dot{Q}_{ch} = \dot{Q}_e + \dot{Q}_{ch}\chi\left(\frac{A_{sw}}{A_f}\right)\frac{\Delta H_{ch}}{L} - \dot{q}''_{loss} A_{sw} \frac{\Delta H_{ch}}{L} \tag{9}$$

This equation can be made dimensionless by dividing each term by $\dot{q}'''_{ch} w^2 d$

$$\frac{\dot{Q}_{ch}}{\dot{q}'''_{ch} w^2 d} = \frac{\dot{Q}_e}{\dot{q}'''_{ch} w^2 d} + \frac{\dot{Q}_{ch}\chi}{\dot{q}'''_{ch} w^2 d}\left(\frac{A_{sw}}{A_f}\right)\frac{\Delta H_{ch}}{L} - \frac{\dot{q}''_{loss} A_{sw}}{\dot{q}'''_{ch} w^2 d}\frac{\Delta H_{ch}}{L} \tag{10}$$

It is convenient to define the following dimensionless variables:

Fire size $$\zeta_f = \frac{\ell_f}{w} = \frac{\dot{Q}_{ch}}{\dot{q}'''_{ch} w^2 d} \qquad (11)$$

Exposure fire size $$\zeta_e = \frac{\dot{Q}_e}{\dot{q}'''_{ch} w^2 d} \qquad (12)$$

Surface heat loss $$\gamma_{loss} = \frac{\dot{q}''_{loss}}{\dot{q}'''_{ch} d} \qquad (13)$$

Parallel panel aspect ratio $$\alpha = d / w \qquad (14)$$

Combustion heat gain $$\Gamma = \frac{\Delta H_{ch}}{L}. \qquad (15)$$

In terms of these variables, the area ratio becomes (assumption 3),

$$\frac{A_{sw}}{A_f} = \frac{2w\ell_f}{2\left(w\ell_f + d\ell_f + wd\right)} = \frac{\zeta_f}{\zeta_f + \alpha\zeta_f + \alpha}, \qquad (16)$$

The governing Equation 10, in dimensionless form becomes

$$. \quad \zeta_f = \zeta_e + \zeta_f\left(\frac{\zeta_f}{\zeta_f + \alpha\zeta_f + \alpha}\right)\chi\Gamma - 2\zeta_f \Gamma\gamma_{loss} \qquad (17)$$

This algebraic equation expresses the parallel panel model in mathematical terms. For each exposure fire ζ_e there is at least one overall fire size ζ_f whose value depends on the three parameters: (1) flame heat transfer, $\chi\Gamma$, (2) surface heat loss, $2\Gamma\gamma_{loss}$, and (3) the aspect ratio, α, of the parallel panel test geometry.

Scaling the Aspect Ratio

One can eliminate any explicit dependence on the aspect ratio, α, in the governing equation 17, with no loss of generality, through use of the following transformation:

Scaled Fire Size $$\phi = \zeta_f\left(1+\alpha\right)/\alpha \qquad (18)$$

Scaled Exposure Fire Size $$\phi_e = \zeta_e\left(1+\alpha\right)/\alpha \qquad (19)$$

Scaled Flame Heat Flux $$\Pi = \frac{\chi\Gamma}{1+\alpha} \qquad (20)$$

Scaled Heat Loss $$\Lambda = 2\Gamma\gamma_{loss} \qquad (21)$$

In terms of these scaled variables the governing Equation 17 becomes

$$\phi = \phi_e + \frac{\phi^2\Pi}{\phi+1} - \Lambda\phi \qquad (22)$$

which no longer explicitly depends on the aspect ratio, α. The aspect ratio, α, remains a very important parameter of the physical problem. It is just that we do not need to explicitly consider it while developing the mathematics.

Equation (22) says that the scaled overall fire size is equal to: (1) the scaled exposure fire size plus (2) the effect of scaled flame heat transfer on the tested material, Π, less, (3) the effect of scaled surface heat loss, Λ. One is generally interested the resultant overall fire size, ϕ, for a given exposure fire size, ϕ_e. One is particularly interested in whether the overall fire size remains finite or runs away with uncontrolled fire spread. This is shown for a scaled surface heat loss, $\Lambda = 0.1$, in Figure 1. In general, if $\Pi < 1+\Lambda$, the fire will not run away, but it might become large for a large exposure fire, ϕ_e. On the other hand, if $\Pi \geq 1+\Lambda$, the fire can potentially run away if the exposure fire, ϕ_e, is big enough. In the latter case (i.e. $\Pi \geq 1+\Lambda$) the critical exposure fire size leading to a run away fire is

$$\phi_e\big|_{crit} = \Pi\left[1-\sqrt{1-\frac{(1+\Delta)}{\Pi}}\right]^2 \tag{23}$$

as shown Figure 2.

The model predictions agreed (without adjustment of parameters) with experimental tests for two fuels PVC(g) and CP-6 given in Table 1 below. Both fuels are quite fire resistive. Predictions for these two fuels for Parallel Panel Test aspect ratios, $\alpha = d/w$ equal to 0.5, 1.0 and 2.0 are given by the final four figures. One sees that both fuels can potentially support a run away fire for a test aspect ratio of 0.5 provided the exposure fire size is intense enough. Neither fuel can support a run away fire for an aspect ratio of 2.0.

Property	Symbol	Unit	PVC(g)	CP-6
Heat of Combustion	ΔH_{ch}	kJ/g	7.0	19.0
Heat of Gasification	L	kJ/g	2.63	5.9
Heat Gain	$\Gamma = \Delta H_{ch}/L$	[--]	2.66	3.22
Surface Heat Loss	$\dot{q}''_{loss}$	kW/m2	12.5	18.4
Surface Temperature	T_s	K	685	755
Surface Enthalpy	$C_p(T_s - T_\infty)$	kJ/g	0.48	0.57
B-Number	$B = \frac{\Delta H_{air} - C_p(T_s - T_\infty)}{L}$	[--]	0.96	0.41
Blockage	$\chi = ln(1+B)/B$	[--]	0.70	0.84
Smoke Yield	$y_s = \dot{g}_{smoke}/\dot{g}_{fuel-vaporized}$	[--]	0.116	0.090
Surface Loss	$\gamma_{loss} = \frac{\dot{q}''_{loss}}{\dot{q}'''_{ch} d}$ $for\ d = 0.3m,$ $\dot{q}'''_{ch} = 2000\,kW/m^3$	[--]	0.0208	0.0307
Scaled Heat Flux	$\Pi = \frac{\chi\Gamma}{1+\alpha},\ for\ \ \alpha = 0.5$	[--]	1.24	1.8
Scaled Heat Loss	$\Lambda = 2\Gamma\gamma_{loss}$	[--]	0.11	0.20

(1) PVC(g) & CP-6 properties evaluated 300s after application of imposed heat flux

(2) $\dot{q}''_{loss} = \sigma(T_s^4 - T_\infty^4)$

(3) $C_p = \mathbf{0.00125}\ kJ/gK$

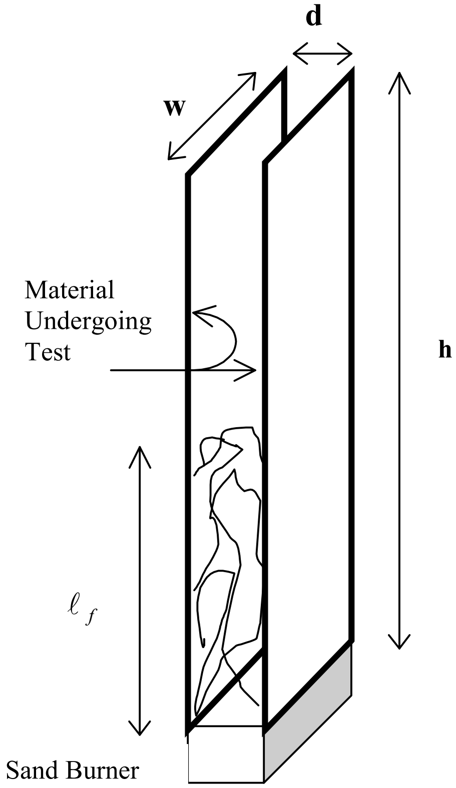


Figure 3 Parallel Panel Test

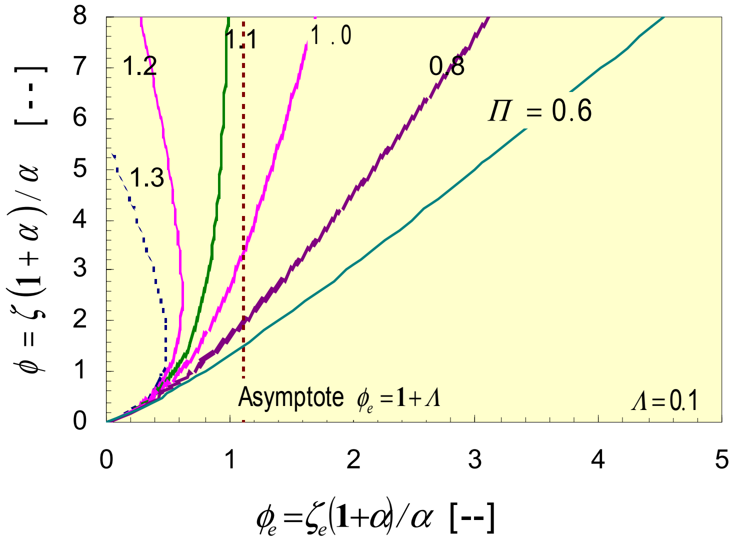


Figure 2 Scaled Fire Size vs. Scaled Exposure Fire Size

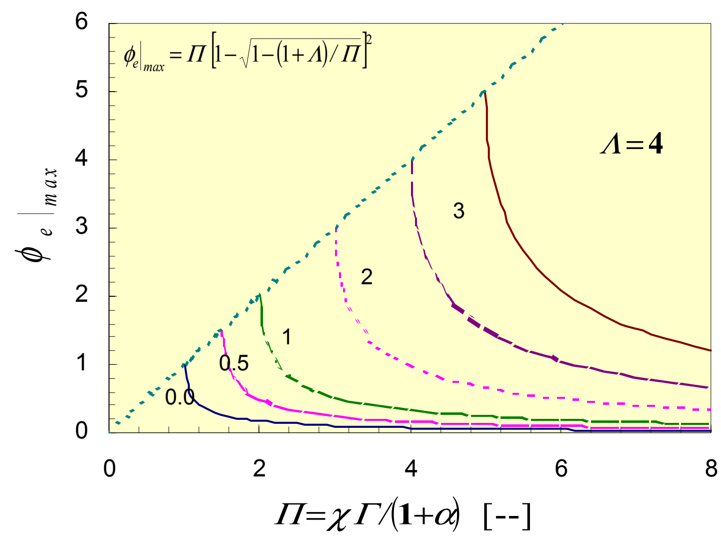
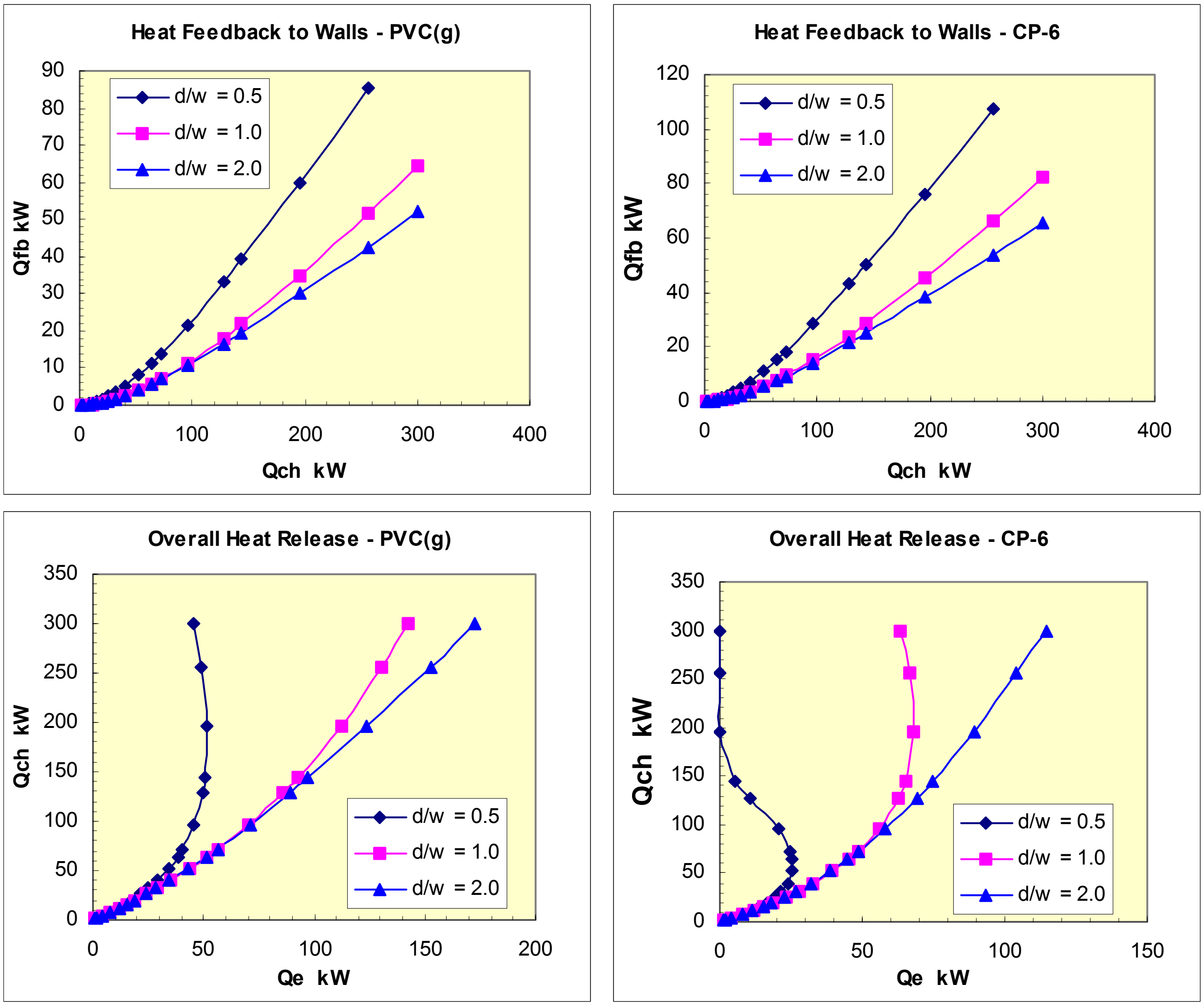


Figure 1 Critical Scaled Exposure Fire Size Leading to Fire Run Away



Figures 4-7 Predicted Heat Feedback and Overall Heat Release Rates vs. Exposure Fire Size of Parallel Panel Test Fires for PVC(G) and CP-6 for Apparatus Aspect Ratios of 0.5, 1.0 and 2.0 for