Upward Fire Spread: Key Flammability Properties, Similarity Solutions and Flammability Indices

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ABSTRACT

Measurement methods and their interpretation are discussed for determining key flammability properties of charring and non-charring materials that are required as an input to a comprehensive Upward Flame Spread and Growth computer model. In addition, desirable similarity situations for upward flame spread are outlined which provide simple analytic solutions for upward flame spread rates. These solutions can be used to provide insight and illustrate how the material properties affect upward flame spread. Among other material parameters (critical heat flux, ignition parameter, χ_R, χ_A), an important parameter is the material flammability number, MFN = $(\chi_R + \chi_C)$. $\Delta H_c / \Delta H_v$, (χ_R radiant fraction and χ_C convective fraction of the heat release rate applied back to the surface, ΔH_c = heat of combustion, ΔH_v = effective heat of gasification), which affects monotonically the ratio of flame height to pyrolysis length. For low values of this parameter (so that $Z_f/Z_p \lesssim 1$), self-sustained flame spread will even stop (except if the material is heated uniformly throughout up to the pyrolysis temperature by an external heat flux).

KEY WORDS: Flame Spread, Flammability.

INTRODUCTION

Upward fire spread is a critical phenomenon for the fire hazard behavior of materials. [1] Upward fire spread rates depend on several interacting phenomena (see e.g. Figure 1) so that prediction of such rates in different scales is difficult. Moreover, relative classification of the upward fire spread rates by using small-scale tests is dubious.

We have developed recently an Upward Fire Spread and Growth (UFSG) simulation [1] which is being used to predict and investigate upward flame spread rates on vertical walls including scale effects. This code has been designed to use as input [1] key flammability properties for a given material measured in existing flammability apparatus. Which are these flammability properties and how they can be determined both for charring and non-charring materials, is discussed in Section II. Special emphasis is given to the transient pyrolysis of materials.

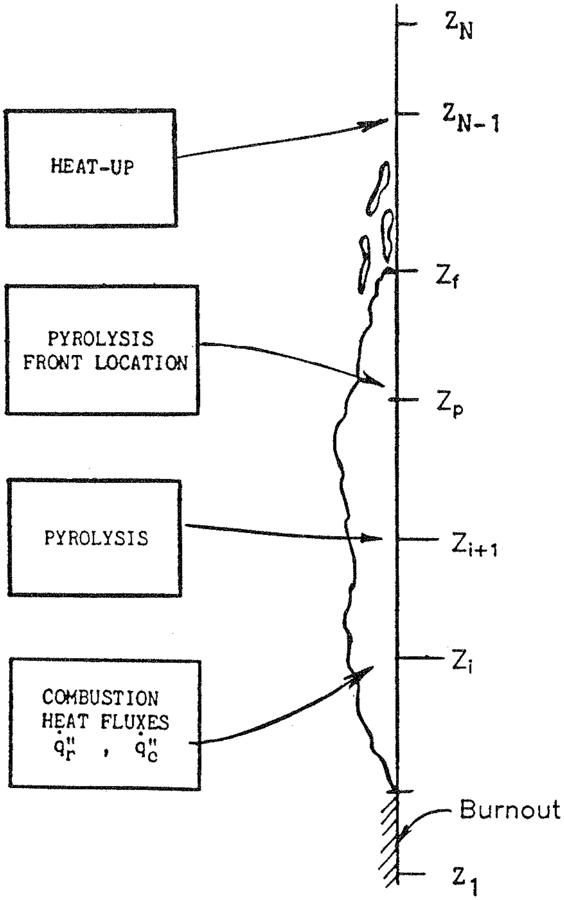

Figure 1. Physical Components of the Upward Fire Spread and Growth Simulation

People also desire, however, simple relationships for upward flame spread rates so that they could obtain a relative (although not general) classification of materials. Such simple expressions exist for similarity situations for upward flame spread which are briefly discussed in Section III. A new similarity solution has been found which represents upward turbulent flame spread over large-scale walls. This situation could allow the determination on a sound basis of the parameters which affect large-scale (radiation dominated) upward flame spread.

KEY MATERIAL FLAMMABILITY PROPERTIES

Table 1 lists the key material flammability properties required for predicting upward flame spread for charring and non-charring materials. These properties are needed for calculating all the components of upward flame spread as shown in Fig. 1, which are implemented in a new Upward Fire Spread and Growth (UFSG) code. [1] Our approach has been to keep the pyrolysis physics as simple as possible, yet retain the essential features governing transient pyrolysis phenomena which significantly affect upward flame spread rates. [1] In consistency with this approach, we model the material thermal response by using a thermal pyrolysis model, i.e. pyrolysis starts when the surface temperature reaches a pyrolysis temperature ($T_s = T_p$) and proceeds at a rate determined by a latent heat of gasification (L) and the heat lost into the solid. For some materials all the solid material transforms to gases, non-charring materials, while for others the solid material transforms to gases and an insulating char matrix, charring materials. The same key flammability properties together with models are planned to be used for explaining the material flammability evaluation from various National tests (Great Britain, France, USA, Germany) so that all these tests could be replaced by a more rational and comprehensive methodology for material fire hazard classification.

We discuss next how the material properties can be, or could be, determined from measurements in existing flammability apparatuses.

Heat-up and Time to Ignition (see Table 1)

From preignition data, one can obtain the thermal properties of the virgin material for both charring and noncharring materials. Such data may include [3,4,5] a) piloted ignition times at various fixed heat fluxes, b) surface temperature histories, and c) mass loss histories. We have recently demonstrated [3,4] how to obtain the thermal inertia of the virgin material ($k\rho c$) and its pyrolysis temperature (T_p) from time to ignition data. Figure 2 summarizes the methodology and the necessary test conditions which are described in detail elsewhere [3,4]. For a thermally thick material covered with 50 μm carbon black, one can obtain the thermal inertia ($k\rho c$), the critical heat flux and the pyrolysis temperature, T_p, as shown in Figure 2 by plotting $1/\sqrt{t_{ign}}$ vs $\dot{q}''$. Other important and practical considerations for test evaluation (finite thickness, in-depth absorption surface reflectivity) can be addressed appropriately in a simple way by an extension of the present test methodology and analysis.

Transient Pyrolysis Data

We have run an extensive experimental program [5] for characterizing the material flammability properties for transient pyrolysis both for non-charring and charring materials. A horizontal sample of a material (12.5 cm diameter) was exposed in an inert N_2 atmosphere to various uniform heat

TABLE 1. KEY FLAMMABILITY PROPERTIES

NON-CHARRING	CHARRING	METHOD OF MEASUREMENT
	Heat-up and Ignition	
K, ρ, C_p	$K_v, \rho_v, C_{p,v}$	1. Time to Ignition [2,4,5]
T_p	T_p	2. Surface Temperature Histories [3]
*	*	3. Weight Loss
	Pyrolysis Transient	
$\Delta H_v, \rho$	$L, \rho_v, C_{p,v}, \rho_c$	Weight Loss Histories
$\Delta H_v = L + C_p (T_p - T_o)$	$d_c = \frac{k_c(T_p)T_p}{4\sigma T_p^4} = \frac{k_c T_p}{4\dot{q}''_{cr}}$	Surface Temperature Histories
	(char conductance depth)	
	Gaseous Combustion	
χ_A	χ_A	Collecting Hood Gas Analysis
ΔH_c	ΔH_c	
χ_R	χ_R	Smoke Point
(T_f,S)	(T_f,S)	

Notes:

a) Subscript v = virgin fuel, c = char layer

b) Critical Heat Flux = $\sigma (T_p^4 - T_o^4) = \dot{q}''_{cr}$

* (Other effects such as reflectivity, in-depth radiation absorption are not currently evaluated (see text)).

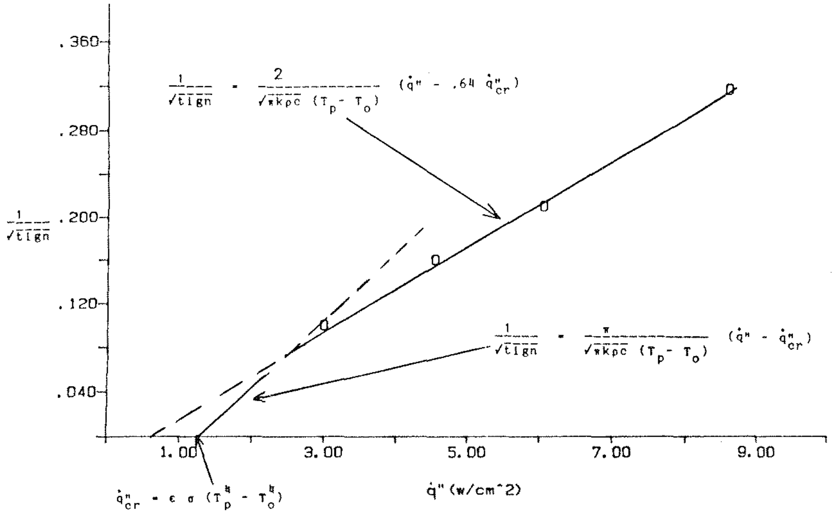

Figure 2. A proper way for plotting time to ignition data for obtaining the thermal inertia (kρc) and the pyrolysis temperature (T_p) as shown from the line through the experimental points. (PMMA sample is covered with 2 mil carbon black.)

fluxes varying from 2 W/cm^2 to 15 W/cm^2. Its surface temperature and its weight loss history for each heat flux were measured. [2,5]

Figures 3 and 4 for the weight loss histories clearly show how one can distinguish whether a material behaves like a "non-charring" (Figure 3) or a "charring" material (Fig. 4).

Another difference between noncharring and charring material concerns the variation of surface temperature with time after pyrolysis starts. For noncharring materials, the surface temperature after pyrolysis starts is constant [5] (e.g. about 640K for PMMA nearly independent of the heat flux). For charring materials, the surface temperature increases with time so that the reradiation losses increase significantly. These reradiation losses control the pyrolysis process in charring materials to the extent that the effects of the thermal capacity of the char are negligible and the char layer effects are characterized and influenced by the char conductivity. These results were definitely demonstrated in recent work, after the completion of the original work in this paper [6]. These results show that the surface temperature for charring materials should be plotted, as shown in Figure 5. Such a plot together with a mathematical model can be used to obtain the char conductivity [6] (see Table 1) or the conductance depth d_c as shown in Table 1. By using the mass loss measurement (see Figure 4) one can then determine the heat of gasification L. (For noncharring fuels the heat of gasification can be determined from Figure 3.)

Our recent work [6] confirmed our approximate solution for large times after pyrolysis, which also agrees with experimental results [6]:

$$\dot{m}'' = \frac{A}{\left(\frac{t - t_p}{t_p}\right)^{1/2}} \qquad \text{fcn } t \gtrsim 2\, t_p \tag{1}$$

where

$$A = \frac{1}{2}\,\frac{\dot{q}'' - \sigma T_p^4}{\Delta H_v}\left(\frac{(1 + \lambda)\, d_c}{\delta_v}\right)^{1/2} \tag{2a}$$

$$\lambda = \frac{\Delta H_v}{C_p\,(T_p - T_o)} \tag{2b}$$

$$\delta_v = \frac{K_v\,(T_p - T_o)}{\dot{q}'' - \sigma T_p^4} \tag{3a}$$

$$d_c = \frac{K_c\,T_p}{4\,\dot{q}''} \tag{3b}$$

$$t_p = \text{pyrolysis time} = \pi/4\;\frac{k\rho c\,(T_p - T_o)^2}{(\dot{q}'' - .64\,\sigma T_p^4)} \tag{3c}$$

Equation (1) has proven useful in the evaluation of fire spread and growth over charring materials, as it will be presented elsewhere.

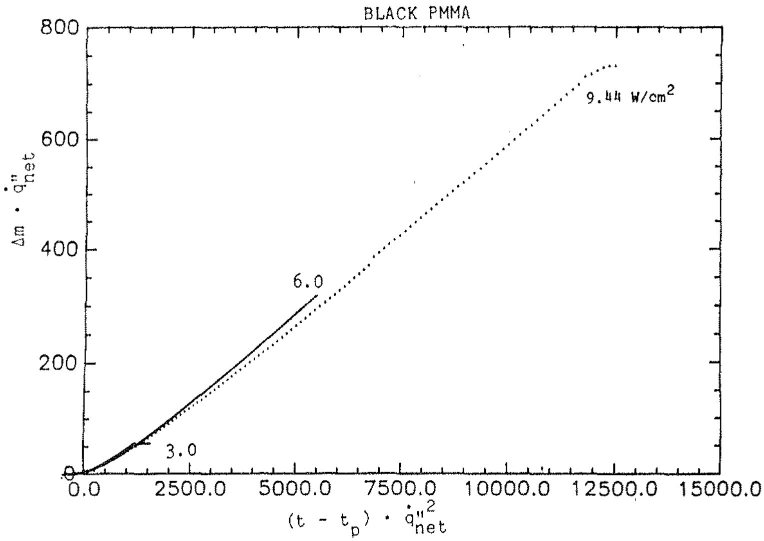

Figure 3. A plot of transient pyrolysis data for non-charring materials which allows the collapse of time history data for various constant heat fluxes (t_p is the time to pyrolysis, $\dot{q}''_{net}$ is the net heat flux = $\dot{q}''_e - \sigma T_p^4$) ($\Delta m$ in g, t in s, $\dot{q}''_{net}$ in W/cm^2).

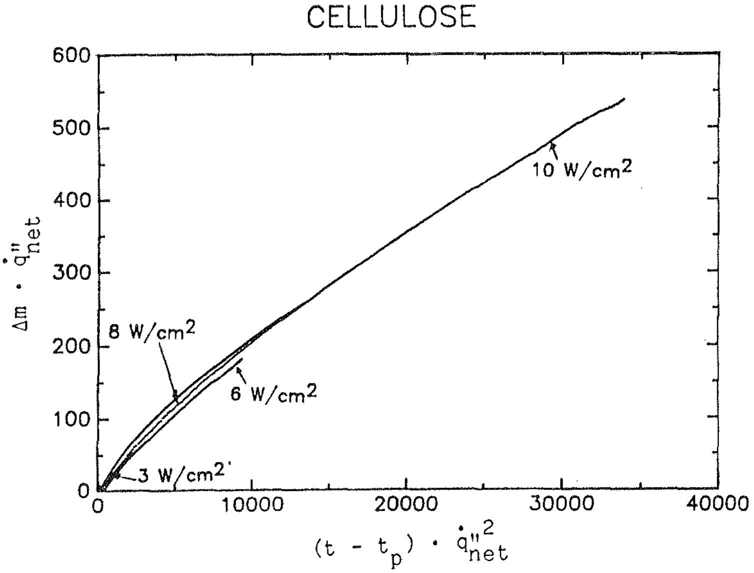

Figure 4. Transient pyrolysis data for a charring material (cellulose made in our laboratory). Same coordinates as in Fig. 4 are used. One should notice the difference in behavior from Fig. 4 (Δm in g, t in s, $\dot{q}''_{net}$ in W/cm^2).

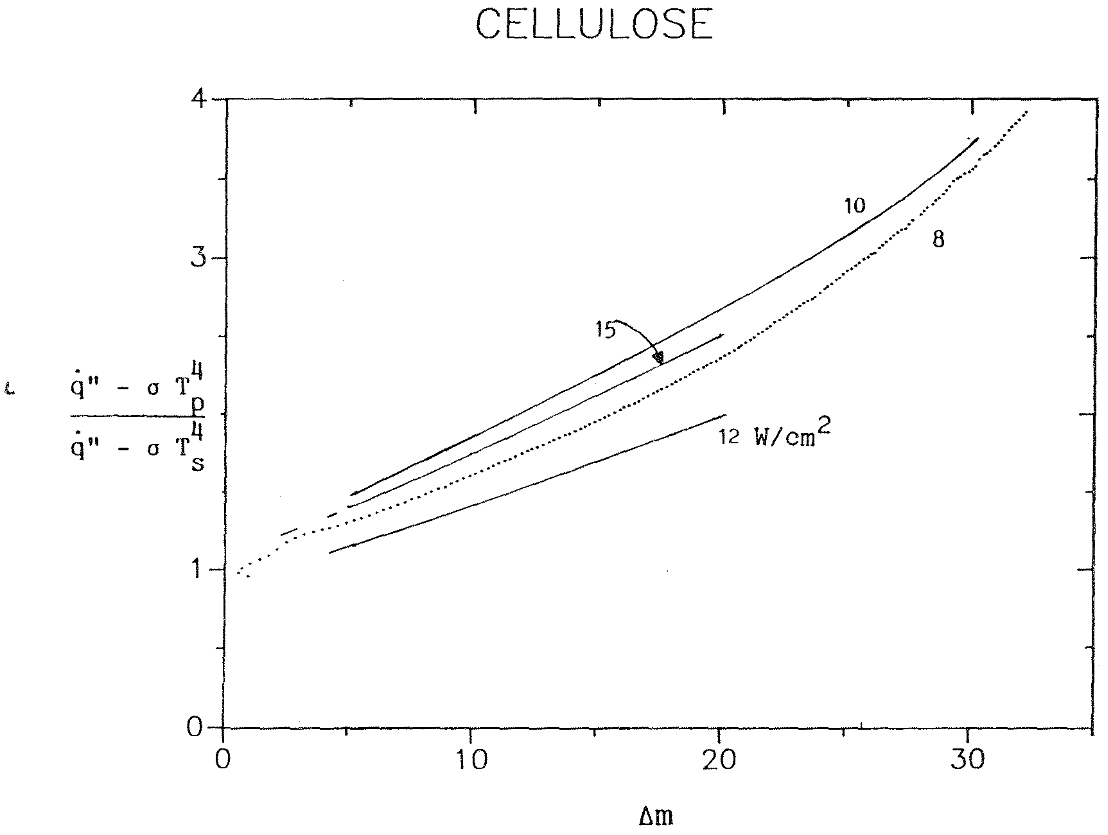

Figure 5. Surface temperature of a charring material plotted vs its weight loss measured at the same time as the temperature. (Here $\dot{q}''$ is the imposed heat flux in kW/m^2, T_s is the surface temperature in K, and T_p is the pyrolysis temperature while Δm is the mass loss in g.)

Gaseous Combustion (See Table 1)

The heat of combustion (ΔH_c) and the effectiveness of combustion (χ_A) are required to determine the flame height and the distribution of the heat flux to the wall. [1] The radiant fraction (χ_R) and the flame temperature and stoichiometric ratio (T_f,S) are needed to calculate the magnitude of the radiative and the convective heat flux to the wall. [1] Such properties (including χ_R) are being measured in existing flammability apparatus by gas analysis. [3,7] The applicability of these experimental results to wall fires has not been completely assessed.

One needs to make the following comments: 1) the effects of mass transfer number, especially for charring materials, on the chemistry (e.g. smoke yield) have to be evaluated by running experiments at low heat flux levels (we estimate that these effects are negligible if $\dot{m}'' > 8$ g/m^{2}s); 2) the importance of the laminar smoke-point height for estimating flame radiation and smoke yield for solid (even PVC type) fuels has to be established. For this purpose a laminar smoke-point apparatus for solid materials has been developed and currently evaluated at FMRC.

SIMILARITY SITUATIONS AND FLAMMABILITY INDICES

The material pyrolysis properties in Table 1 are sufficient inputs in a new upward fire spread and growth (UFSG) code. [1] This code has already been used to predict upward fire spread on non-charring materials whose properties can be deduced from standard test measurements as demonstrated in Section 2.1 and 2.2 (see also Figs. 2, 3 and 4). An important results from this application of the code [8] is that transient pyrolysis for non-charring materials (see the initial part of the curves in Fig. 3) significantly affects the fire spread rate. The magnitude of transient pyrolysis effect [8] depends on the ratio $L/C_p(T_p - T_o)$.

Application of the UFSG code [1] to turbulent upward flame spread experimental data [12] on PMMA has led us recently to significant results and insight. In this situation (see Figure 1), the heat flux (radiative and convective) to the surface over the extent of the flame has been measured to be constant [13] over a pyrolysis length of about 1.5 m ($q'' \simeq 30$ kW/m^2). Numerical results and comparison with experiments have shown (after considerable hindsight) that the pyrolysis location, Z_p, is correlated as (these results will be presented in detail elsewhere):

$$\frac{Z_p}{\ell} = \text{fcn}\left(\frac{t}{t_p}, \frac{Z_{p_o}}{\ell}\right) \tag{4a}$$

The functional relationship in eq. (4a) is too complicated to be presented in this paper. Here Z_{p_o} is the initially pyrolyzing region, where t_p is a pyrolysis time (see eq. (3c)) and ℓ is a characteristic length scale related to the combustion process:

$$\ell \sim \left[\dot{q}'' \left(\frac{\Delta H_c}{\Delta H_v}\right)\right]^2 \tag{4b}$$

(The proportionality constant accounts for the proper dimensions, it involves gravitational acceleration and ambient air properties.) This length can be derived from the flame height relationship [13]:

$$Z_f \sim \dot{Q}'^{2/3} \sim \left[\dot{q}'' \frac{\Delta H_c}{\Delta H_v} Z_p\right]^2 \tag{4c}$$

if one sets $Z_f = Z_p = \ell$ in this equation.

Another case concerns the flame spread on large-scale wall fires ($Z_p > 3$ m). In this case the heat feedback to the surface is expected to be a constant radiative fraction of the heat release rate [9] so that:

$$\dot{q}'' \sim \chi_R \frac{\dot{Q}'}{Z_f} \tag{5a}$$

(but a maximum value of $\dot{q}'' < 60$ kW/m^2 must be imposed as the flame becomes optically thick). In this case there is no characteristic length scale and one can derive by using eq. (4c) (both equalities) that:

$$\frac{Z_f}{Z_p} \sim \chi_R \frac{\Delta H_c}{\Delta H_v} \tag{5b}$$

A similarity solution (for noncharring materials) exists for this situation but it will be presented elsewhere. (For clarification a similarity solution exists if the flame spread rate can be expressed as $t_p/Z_p \, dZ_p/dt$ = fcn (Z_f/Z_p) wherein t_p is a characteristic pyrolysis time.)

The present experimental and analytical results (eq. (4a), (4b), (4c)) confirm the importance of the parameter

$$\dot{q}'' \frac{\Delta H_c}{\Delta H_v} \tag{6a}$$

or equivalently $\chi_R \frac{\Delta H_c}{\Delta H_v} = \text{MFN}$ (6b)

the so-called material flammability parameter number, on flame spread processes. The time to pyrolysis, t_p, is the other important parameter (see eq. (4a)).

The same methodology (i.e. using the UFSG [8]) is being extended to charring materials; these results, however, will be presented elsewhere, together with burnout effects and comparison with experiments. [9]

CONCLUSIONS

The important contributions and conclusions of this work are:

1. Key flammability properties for charring and non-charring materials can be derived by a validated methodology from measurements in existing flammability apparatuses, including the transient pyrolysis for charring materials. These properties are being used in a new Upward Fire Spread and Growth [1] simulation.
2. New similarity solutions for small- and large-scale turbulent upward flame spread have been obtained. These solutions demonstrate which parameters affect upward flame spread rates.
3. Among these parameters (e.g. ignition time, t_p, χ_R, χ_A), a very important parameter is the material flammability number MFN = $\chi_R \, \Delta H_c/\Delta H_v$ which is related to the ratio of the flame height, Z_f, to pyrolysis length, Z_p.

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