Ignitor and Thickness Effects on Upward Flame Spread

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ABSTRACT

Several studies have developed upward flame spread models which use somewhat different features. However, the models have not considered the transient effects of the ignitor and the burning rate. Thus, the objective of this study is to examine a generalized upward flame spread model which includes these effects. We shall compare the results with results from simpler models used in the past in order to examine the importance of the simplifying assumptions. We compare these results using PMMA, and we also include experimental results for comparison. The results of the comparison indicate that flame velocity depends on the thermal properties of a material, the specific model for flame lemgth and transient burning rate, as well as other variables including the heat flux by ignitor and flame itself. The results from the generalized upward flame spread model can provide a prediction of flame velocity, flame and pyrolysis height, burnout time and position, and rate of energy output as a function of time.

1. INTRODUCTION

Upward flame spread on vertical surface is a critical aspect of accidental fires because of its inherent high speed and potential consequences of fire growth to surroundings. Most of the principal researchers in the area of fire have devoted significant effort in trying to extend the knowledge on the mechanisms controlling flame spread and mass burning to represent this hazard and attempt to assess the relative contribution for a material. Here this research is interested in the effect of an ignitor, thermal inertia($k\rho c$) of a material, and burnout during flame spread.

Saito, Quintiere and Williams[1] developed a flame spread model which includes the relationship between flame height, pyrolysis height, and characteristic ignition time. In this model, flame height is controlled by heat released per unit mass of fuel consumed and mass loss rate per unit area, pyrolysis height depends on flame velocity, and characteristic ignition time is dominated by $k\rho c$ of a material. They assume that the ignitor effect is zero, which means after ignition, mass loss rate is constant, that is steady burning. In other words, the ignitor effect, burnout effect, and unsteady burning are not included in the solution.

The objective of this research is to develop transient flame spread model which utilizes the numerical solution based on the formulation outlined by Saito, Quintiere and Williams[1]. The model will be dependent on the different $k\rho c$ values of a material. The model will be applied to a thermoplastic. Specifically, this research examines the model using polymethylmethacrylate(PMMA), as an example.

The ultimate goal of the research is to examine the flame spread model, which includes the ignitor effect, burnout effect, and transient burning rate model performed by Hopkins[8], using the data obtained by some researchers[11,12,13] in the program and comparing the results with the experimental results of Orloff, de Ris, and Markstein[11]. The generalized results should provide more accurate predictions in terms of flame spread because it includes transient effects. Using the model we can predict the flame height, pyrolysis height, flame velocity, burnout position and time, total energy release rate at a specific time.

2. Derivation of Flame Spread Model

Description of Spread Mechanisms

Flame Spread occurs as a consequence of heating of the unignited portion of the fuel to a temperature at which vigorous pyrolysis begins. This heating is produced by convective and radiative heat transfer from the flames that bathe the fuel surface. Let x denote the vertical distance along the fuel surface, with x=0 at the base of the fuel, $x=x_p$ at the upper edge of the pyrolysis region and $x=x_f$ at the average height of the visible flame tip. The heat transfer responsible for spread occurs in the region $x \geq x_p$. For steady-state burning at the base of a vertical wall, the energy flux $\dot{q}''$ to the wall has been found experimentally[2] to correlate with x/x_f, and in a rough first approximation for $\dot{q}'' = \dot{q}''_o$ = constant ≈ 2.5 W/cm^2 for $0<x<x_f$ and $\dot{q}''=0$ otherwise, so that x_f is a good measure of the distance over which the principle heat transfer occurs.

If this rough approximation is employed along with the further assumption that $x_f - x_p$ remains approximately constant during spread, then the upward spread velocity of pyrolysis front is

$$V_p = 4(\dot{q}_o'')^2 (x_f - x_p) \,/\, [\pi k\rho c(T_p - T_a)^2] \ , \qquad (1)$$

where k, ρ, c are the thermal conductivity, density and heat capacity, respectively, of the fuel, and T_a and T_p are the ambient and ignition(or pyrolysis) temperatures of the fuel. Therefore, Equation (2.1.1) can be rewritten as

$$V_p = \frac{x_f - x_p}{\tau} \ , \qquad (2)$$

where, $$\tau = \frac{\pi}{4} k\rho c \left\{\frac{T_p - T_a}{\dot{q}_o''}\right\}^2 \ ,$$

the characteristic ignition time τ for spread depends only on fuel properties, the ambient temperature and the level of the heat flux to the fuel from flame. As a simplification for describing time-dependent spread, we assume that Eq.(2.1.2) continues to apply with $x_f - x_p$ variable and that τ remains an approximately constant time characteristic of upward spread.

Flame-Height Correlations

Having hypothesized that the correlation of the heat-flux distribution with x/x_f may lead to Eq.(2.1.2), we need an expression for $x_f - x_p$ to obtain V_p. By definition

$$x_p(t) = x_{po} + \int_0^t V_p(t_p)\,dt_p \ , \qquad (3)$$

where x_{po} is the value of x_p at an initial time t=0, and t_p is the dummy variable of integration. Flame-height correlations are required for obtaining x_f. The total rate of energy release per unit length is the sum of

$$\dot{Q}' + q\int_0^x \dot{m}''dx \ , \tag{4}$$

where $\dot{Q}'$ is the energy release rate per unit length at the base of the wall, $\dot{m}''$ is the rate of mass loss per unit area of the fuel, and q is the heat released per unit mass of fuel consumed. Flame-height correlations are of the form

$$x_f = k_f[\dot{Q}' + q\int_0^{x_p} \dot{m}''dx]^n \ , \tag{5}$$

where k_f, flame height coefficient, and n are constants. The flame height for wall flames is given such that $k_f = 0.067$ $(m^5/kw^2)^{1/3}$ and n=2/3, or approximately $k_f = 0.01$ (m^2/kw) and n=1[2],[3],[4].

3 The Theory of Generalized Flame Spread Model

We have discussed flame height and flame velocity after ignition and under constant mass loss rate. In general, flame height and velocity, however, can be affected by the ignitor, burnout, and transient burning rate. Therefore, we need a general model that includes the effect of an ignitor, burnout, and burning rate to analyze and predict a real fire situation. The model will be described below.

Flame Height Calculations

Flame spread can be separated with three part, before ignition, after ignition and after burnout respectively. Flame height is solely due to the ignitor before an ignition occurs. Its flame height can be computed or experimentally determined according to its configuration[7]. The flame height after wall ignites due to $\dot{Q}_{ig}$ and $\dot{Q}'$ up to burn out of the initial region ignited($t_{ig} \le t < t_b(x_{fig})$). At this situation flame height becomes

$$x_f(t) = k_f\left[(\dot{Q}_{ig} \ / \ W) + \dot{Q}'\right]^n , \tag{6}$$

where $\dot{Q}'$ is the wall contribution. The flame spread after initially ignited burn out($t \ge t_b(x_{fig})$). At this time flame height can be written as

$$x_f(t) = x_b(t) + k_f(\dot{Q}')^n \ . \tag{7}$$

Representation for the wall contribution ($\dot{Q}'$) and Burning Rate

The wall contribution can be expressed as

$$\dot{Q}' = \Delta H_c \cdot \int_0^{x_p(t)} \dot{m}''(x)\,dx \ , \tag{8}$$

where ΔH_c is the heat of combustion of a material. From previous work[8], we have an implicit formula for $\dot{m}''(t)$ at x,

$$\dot{m}''(\theta)\Delta H_v = \dot{q}_f'' - \sigma T_{ig}^{\ 4} - \frac{2k}{\delta}(T_{ig} - T_\infty), \tag{9}$$

and $$\theta = t - t_p(x) = \frac{\delta_s^2}{6\alpha}\frac{\Delta H_v}{L}\left[\frac{\delta_{ig}-\delta}{\delta_s} - \ln\left(\frac{\delta_s-\delta}{\delta_s-\delta_{ig}}\right)\right] , \qquad (10)$$

where, $$\delta_s = \frac{2kL}{c(\dot{q}''_f - \sigma T_{ig}^4)} , \qquad (11)$$

$$\delta_{ig}(x) = \sqrt{6\alpha(t_p(x) - t_f(x))} , \qquad (12)$$

The burning rate model assumes flame heating commences at $t_f(x)$, and ignition occurs at $t_p(x)$. Each position x has its own burning history as shown figure 5.3. Note $t_f(x)$ is the time that x first experiences a heat flux due to the flame tip reaching x. The flame spread model assumes a uniform heat flux $\dot{q}''_f$ from x_p to x_f and zero heat flux beyond x_f, that is $x>x_f$. Thus the flame spread model is

$$V_p = \frac{dx_p}{dt} = \frac{x_f - x_p}{\Delta t_f} , \qquad (13)$$

where, $\Delta t_f = \frac{\pi}{4} k\rho c \left(\frac{T_{ig} - T_\infty}{\dot{q}''_f}\right)^2$, a flame spread time,

is constant for a given material.

Burnout Effect

We must limit $\dot{m}''$ due to burn out. Burnout occurs after a duration $\theta_b(x_{fig})$ that is the duration for $x=x_{fig}$ the initial value. Hence the time for burnout is

$$t_b(x_{fig}) = \theta_b(x_{fig}) + t_{ig}, \qquad (14)$$

The burnout position($x_b(\tau)$) can be found as

$$x_b(\tau) = 0 \qquad \text{for } \tau < \tau_b(0), \qquad (15)$$

which is before burnout of region $0 \le x \le x_{fig}$, or

$$x_b(\tau) = x_p(\tau') \qquad \text{for } \tau \ge \tau_b(0), \qquad (16)$$

which is after burnout of region $x_{fig} \le x \le x$.

4. Comparison of Results

The velocity of flame spread is related to the pyrolysis front position of material, $x_p(i)$, the flame tip position, $x_f(i)$, and the characteristic ignition time, τ, that is affected by $k\rho c$. In this section we compare the relationship between x_p and x_f and the relationship between V_p and x_p of the exact solution for n=1, n=2/3, and the generalized flame spread model with the results that others found for PMMA.

The Relationship between x_p and x_f

Orloff, de Ris, and Markstein :

$$x_f = 1.95\, x_p^{0.781} \qquad (17)$$

Exact solution :

$$x_f = 2.4\, x_p \,, \quad \text{for } n=1 \,, \tag{18}$$

and

$$x_f = 2.59\, x_p^{\,0.667} \,, \quad \text{for } n=2/3 \,. \tag{19}$$

Delichatsios, Mathews, and Delichatsios[13] :

$$x_f = 2.01\, x_p^{\,0.667} \,. \tag{20}$$

The Relationship between Vp and x_p

Orloff, de Ris, andMarkstein :

$$V_p = 0.00441\, x_p^{\,0.964} \,. \tag{21}$$

Exact solution :

$$V_p = 0.01448\, x_p \,, \quad \text{for } n=1 \,, \tag{22}$$

and

$$V_p = 0.0103(2.59\, x_p^{\,0.667} - x_p) \,, \quad \text{for } n=2/3 \,. \tag{23}$$

LIFT data :

$$V_p = 0.009283\, x_p \,, \quad \text{for } n=1 \,, \tag{24}$$

and

$$V_p = 0.00663(2.59\, x_p^{\,0.667} - x_p) \,, \quad \text{for } n=2/3 \,. \tag{25}$$

Comparisons and Results

Figure 1 is the result of the comparison of flame height and pyrolysis height between the exact solutions and the experiment and the generalized flame spread model. These curves in figure 1 show the effect of the different flame height coefficient and power to the flame height. Figure 2 is the result of the comparison of flame velocity and pyrolysis height between the exact solutions and the experiment and the generalized flame spread model. These curves in figure 2 also show the effect of the different kρc and ignition temperature(T_{ig}) to the flame velocity.

5. The Effect of Thickness and the Ignitor on Flame Spread

Using the generalized flame spread model with kρc=1.02 kW^2s/m^4C^2 and the properties described by Quintiere and Rhodes [6] in Appendix C, we try to find the effect of thickness and the ignitor on flame spread in this section. A study on the effect of thickness and the ignitor include variations of thickness(mm): 0.1, 0.5, 1.0, 3.0 ; ignitor duration(s) : 30, 60, 120, 480 ; $\dot{Q}'_{ig}$(kW/m) : 10, 25, 50 or correspondingly x_{po} (m) : 0.2, 0.5, 1.0. Figure 3 shows the critical values of the parameters on propagation to 5 m. It is clear that all of these factors play a critical role in propagation.

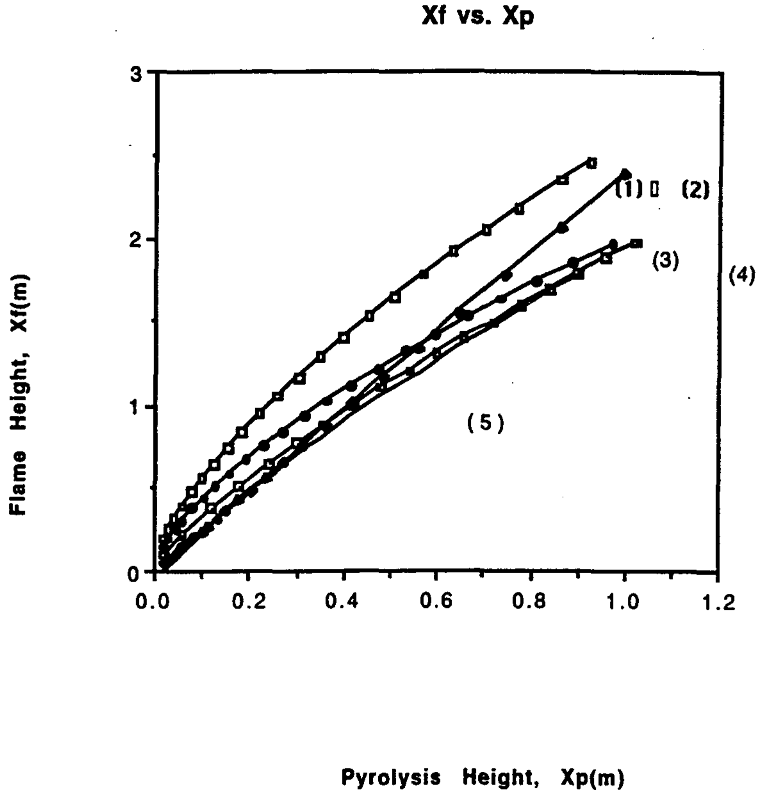

FIGURE 1 The comparison of flame height vs. pyrolysis height

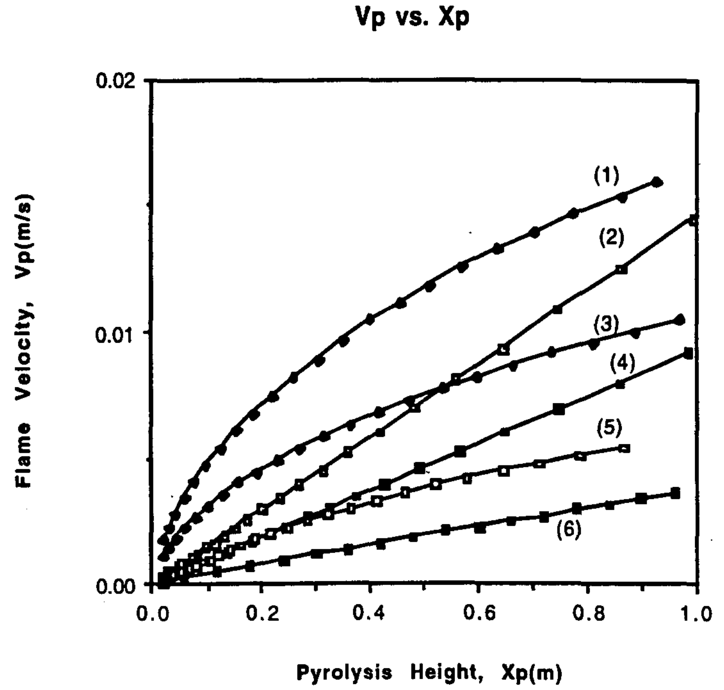

FIGURE 2 The comparison of flame velocity vs.flame height.

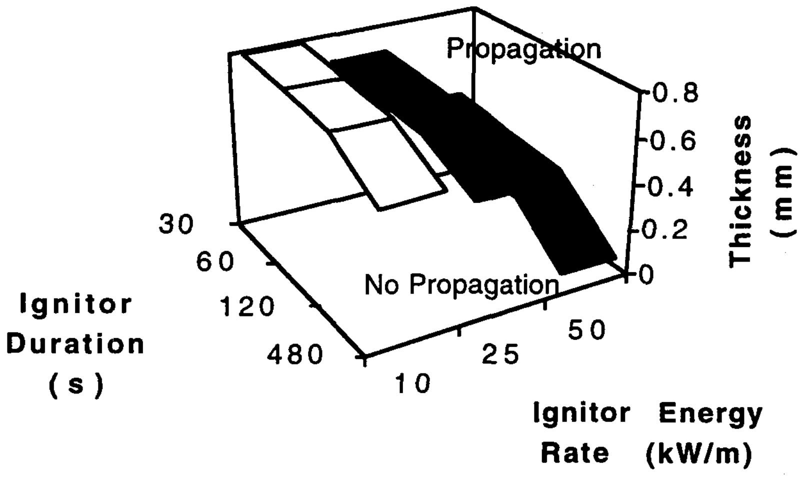

FIGURE 3 Estimated critical values for propagation to 5 m.

6. Conclusions

1. A model for wind-aided flame spread has general acceptance, but selection of material properties and the selection of the flame height function can significantly influence the predicted results. However, all of the solutions do follow the general trend of the the data for thick noncharing PMMA wiht $V_p \sim x_p^m$ where m can vary from 2/3 to 1. By appropriate selections of properties and flame height, the solution can be made to fit experimental data.

2. Upward flame spread propagation signficantly depends on material burn time and ignitor characteristics. As ignitor effects become small the simple criterion for propagation in Table 4 can adequately show the behavior in terms of material properties. In addition, propagation is enhanced as the ignitor becomes larger and remains on longer after ignition.

3. The importance of accelerating flame spread in fire growth shows the need to be able to understand conditions for propagation in terms of both material properties and ignitor characteristics. Test which measure material flammability properties or tests which are based on a specific ignition scenario are not sufficient to examine the full potential for fire growth.

4. This study used a complex model to arrive at its propagation results based on numerical computations. While such solutions include more complete features, simple approximate solutions are needed to produce easily useable formulas for flame spread and propagation criteria. However, these simple results will need to be supported by data. The correlation for propagation to flashover in the room-corner tests demonstrate the feasibility of acheiving simple useable results.

NOMENCLATURE

k - thermal conductivity
T - temperature
Δt - spread time
Q - power output
ρ - density
t - time
x - position
K_f - flame height coefficient
c - specific heat
τ – time
q - heat of combustion

m - mass
L - heat of gasification
ΔH_c - heat of combustion
h - time step
σ - Stefan Boltzmann constant
V - velocity

α - thermal diffusivity
ΔH_v - heat of vaporization
ℓ -thickness
n - power
ε - tolerance for convergence
δ - thermal penetration depth
i,j - dummy variables

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