UPWARD FLAME SPREAD ON PRACTICAL WALL MATERIALS

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ABSTRACT

Models of upward flame spread have been attempted in the past, but in the current work an emphasis has been placed on developing a practical model that will be useful across a broad range of materials. Some of the important aspects of the model are: the addition of external radiation to simulate a wall that is a part of an enclosure fire and has flaming walls radiating to it, the use of a correlation for flame heat feedback distribution to the sample surface based on data available in the literature, and the use of an experimentally measured mass loss rate for the sample material. In this paper, the development of the numerical model is presented along with predictions of flame spread for three materials: hardboard, a relatively homogeneous wood-based material; plywood, which is made of laminated wood bonded by adhesives; and a composite material made of fiberglass matrix embedded in epoxy. Predictions are compared with measured data at several levels of external radiation for each material. For the materials tested, the model correctly predicts trends and does a reasonable job predicting flame heights. The need for thermal property data for practical materials, which would be appropriate for flame spread models, is indicated by this work.

INTRODUCTION

Most compartment fires involve burning of vertical walls made of such combustible materials as wood panels, decorative plastic sheets, or composite materials, which exhibit combustion characteristics that are significantly different from an idealized semi-infinite thick wall. Also, when the wall is subjected to radiative heat flux from an external source such as surrounding fire, upward flame spread can be substantially different from that without external radiation. It has been observed that certain materials which do not sustain upward flame spread in the absence of external radiation flux (for example, wood), sustain flame spread when assisted by an external radiation source [1]. Also, it is expected that materials which normally exhibit upward flame spread will have a significant enhancement in flame spread and fire growth in the presence of external radiation [2,3]. Some of the standard tests such as ASTM E 162 for horizontal flame spread [4] and ASTM E 648 for downward flame spread [5] have indicated that materials which are normally considered safe may exhibit unacceptable behavior under a real fire situation.

This paper presents results of a study on upward flame spread over practical wall materials with and without external radiation heat flux, with an emphasis on developing an analytical model for the flame spread process. The model is based on fundamental principles of flame spread, but it also uses certain available experimental correlations and applied properties measured in independent small scale experiments to account for important aspects of combustion of practical materials. Experimental data on turbulent upward flame spread experiments is also presented for some materials to illustrate capabilities of the model.

DEVELOPMENT OF A MATHEMATICAL MODEL

A slab of material is subjected to a known, external heat flux on its face, and is ignited at the bottom using a line burner. Because of the heat flux provided by flames of the burner and the external heat flux, the surface temperature of bottom section of the wall begins to rise. When the surface temperature reaches a certain characteristic temperature, T_{ig}, the material starts pyrolyzing significantly. Then, flames from the burning of pyrolyzed fuel cover the solid fuel above the pyrolysis front (x_p), which is heated by the energy feedback, $\dot{q}''_f(x,t)$, from the flames and the external radiation sources. When unburned fuel heats up to T_{ig}, it starts pyrolyzing and the flames grow taller, which makes the process of upward flame spread continued. External radiation affects upward flame spread primarily in two ways. The radiant heat flux adds to the heat feedback from the flame and causes the yet-unburned surface of the sample to heat up to the pyrolysis temperature more quickly. Over the surface area that is already burning, the external radiation increases the mass loss rate of the sample which in turn causes longer flames. Important parameters and processes contributing to the upward flame spread, therefore, are the heating of the unburned fuel above the pyrolysis edge, the total heat feedback to the unburned wall surface, $\dot{q}''_w(x,t)$, the flame tip height, x_f and the local mass loss rate of the wall on the pyrolyzing surface, $\dot{m}''$. Thus, the model for describing the upward flame spread process is developed in these four major parts.

(i) *Heating of the yet-unpyrolyzed section of the wall*: It is well established that the flame spread process depends on how fast the unburned fuel ahead of the pyrolysis front can be heated to a critical temperature (or a range of temperature) that causes significant pyrolysis. The surface temperature as well as the inner temperature of the two-dimensional vertical wall, initially at the temperature of T_o, are obtained by solving the transient two-dimensional heat conduction equation with transient boundary condition,

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

Initial Condition : $T(x,y,0)=T_o$

$T(x,0,t)=T_{ig}$ for $x<x_p$

Boundary Conditions : $-k\left|\frac{\partial T}{\partial y}\right|_{y=0}=\dot{q}''_w(x,t)$ for $x>x_p$

$$-k\left|\frac{\partial T}{\partial y}\right|_{y=D}=h(T-T_o)$$

$$-k\left|\frac{\partial T}{\partial y}\right|_{x=0}=-k\left|\frac{\partial T}{\partial x}\right|_{x=H}=0$$

where $y = 0$ to D and $x = 0$ to H represents the domain for calculations. The thermal conductivity k is taken as an average value for the material. (In general, k can vary with the depth for laminated or composite materials. In the present work, a single value reported in literature is used for the materials studied.) With the time-dependent boundary conditions, use of many one-dimensional equations or single two-dimensional conduction formulation require about the same computation time. The 2-D equation is preferred because it gives slightly better accuracy (especially around the pyrolysis edge area where there is temperature gradient in the x direction), and easier definition of computation domain. It is assumed that the ignition temperature does not vary with location, the material is inert during the heating process, and the heat loss to the backside of the wall is in the form of convection to the ambient atmosphere.

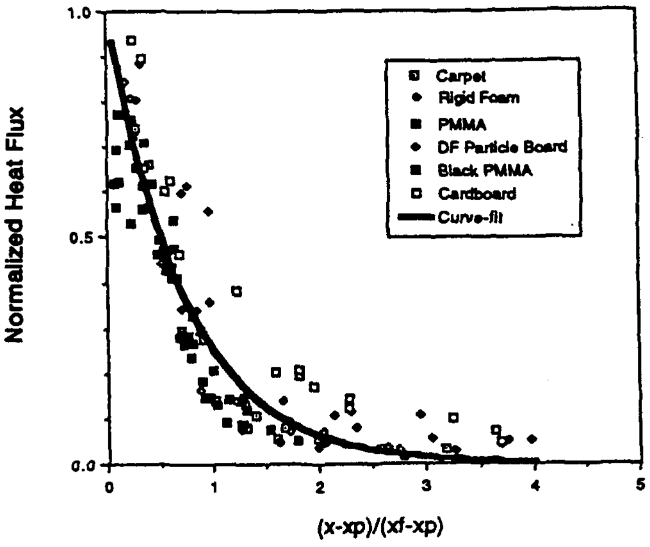

Fig. 1. Correlation for Heat Feedback.

(ii) Total heat feedback, $\dot{q}''_w(x,t)$: This is the heat feedback to the wall above the pyrolysis front and it is responsible for raising the surface temperature of the wall to the critical value which causes *significant pyrolysis*. It is modeled as,

$$\dot{q}''_w = \dot{q}''_f + \dot{q}''_{er} - \dot{q}''_{rerad} \tag{2}$$

where $\dot{q}''_f$ is the flame heat feedback, and $\dot{q}''_{er}$ is the external radiation incident to the wall, and $\dot{q}''_{rera}$ is the heat loss because of surface reradiation from the wall.

In previous studies, $\dot{q}''_f(x,t)$ has been assumed to be constant, typically equal to 25 or 30 kW/m^2, up to a certain height and then zero above[7]. Analytical derivation of $\dot{q}''_f(x,t)$ involves use of several thermal/physical properties in order to estimate the heat flux for a given material. However, the properties are often not available, or the available properties are not known with sufficient accuracy. Therefore, in the present work, $\dot{q}''_f(x,t)$ was obtained from measured data in order to allow its adequate representation. Fig.1 shows measured heat feedback data for black PMMA, clear PMMA, cardboard, Douglas-fir particle board, rigid polyurethane foam, and carpet.[9, 10] The best fit function for these sets of data when expressed in the appropriate dimensionless variable was an exponential decay, given by

$$\dot{q}''_f(x,t) = \dot{q}''_{f0} \exp\left[-C_0\left(\frac{x - x_p}{x_f - x_p}\right)\right] \tag{3}$$

where $\dot{q}''_{f0}$ is the maximum heat feedback from flames to a surface and the decay factor C_O was determined to be –1.37. Values of $\dot{q}''_{f0}$ for two of materials which will be discussed later in the paper are: hardboard, 49.0 kW/m^2; and plywood, 34.8 kW/m^2. The above correlation allows determination of $\dot{q}''_f$ based on a single value of $\dot{q}''_{f0}$ which may be treated as a "fire property" of the wall material.

(iii) Instantaneous flame height : The equation for forward heat flux requires an expression for flame height, x_f. Flame size depends on the cumulative energy release rate which may be calculated by the integration of local burning rate over the entire pyrolyzing region on the wall. The larger the total energy release rate, the taller are the flames, and a greater area ahead of the pyrolysis front is preheated. The flame tip height is obtained from an available correlation[6],

$$x_f(t) - x_p(t) = K\left[\dot{Q}'_b + \dot{Q}'_m\right]^n \tag{4}$$

where the bracket represents the total energy release rate in the fire which is the sum of the energy release rate by the igniter ($\dot{Q}'_b$ in kW/m) and the energy released due to pyrolyzing surface ($\dot{Q}'_m$ in kw/m). Experimental Correlation factor K and n were determined as 0.433 and 2/3 respectively[11].

(iv) Transient local mass loss rate or burning rate, $\dot{m}''$ (t) : To close the model, an estimate of total energy release rate is needed. The total energy release rate at any instant is obtained from the total mass loss rate of the burning slab multiplied by the average heat of combustion of pyrolyzed fuel,

$$\dot{Q}'_m = h_C \int_{x_b(t)}^{x_p(t)} \dot{m}''\, dx \tag{5}$$

The total or cumulative mass loss rate is calculated by integrating the local mass loss rate over the entire burning area. From the flame spread point of view, the history of local burning rate is a characteristic of the combustion behavior of the material and it depends on the physical, chemical and geometric properties of the wall material. For a slab of a homogeneous material like PMMA, the rate of burning initially increases because the heat loss to the interior decreases, then it passes through a maximum value, and finally drops to zero due to heat loss from the back side of finite thickness samples.[12] In the simplest form, $\dot{m}''$ has been assumed to be constant until all the combustibles mass is pyrolyzed; other form have employed inverse square root or exponentially decreasing dependence.

In the present work $\dot{m}''$ (t) is obtained from separate small scale mass loss rate experiments. During the upward flame spreading process, the unburned fuel just above the pyrolysis front is continuously covered by turbulent flames emerging from the pyrolyzing region below. Therefore, the local, transient mass loss rate measured while a material sample is continuously covered by turbulent flames and subjected to the external radiation heat, is taken to be the representative combustion behavior of the material and it is expected to be only weakly dependent on the location. Quantifying the energy release rate experimentally appeared most reasonably for complex materials that burn with their own

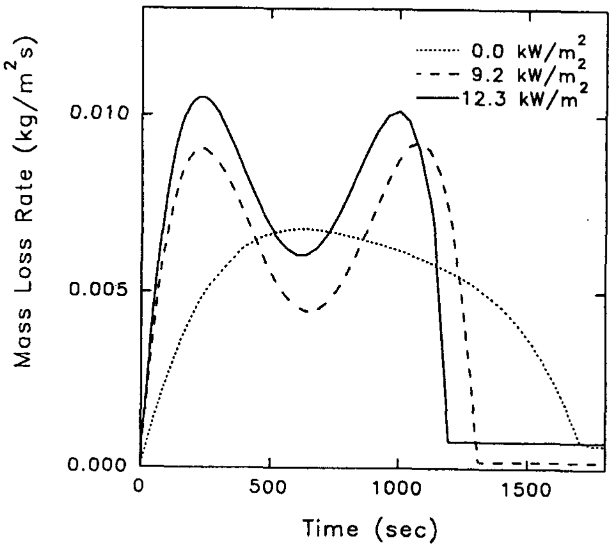

Fig. 2. Mass Loss Rate for a Wood-based Material.

"signature". Figure 2 shows the mass loss rate curves derived from experiments at three levels of external radiation for a typical wood-based materials. These local mass loss rate functions are used in the present calculations. Further details on these experiments and their justification for use in flame spread models, are in reference[13].

Equation (1) through (5) from a complete set of equations with appropriate boundary conditions. The general solution procedure is as follows: at any given instant, t, the local burning rate, $\dot{m}''$, is computed; it is then integrated over $x = x_b$ to $x = x_p$; then the total heat release rate, flame height, and $\dot{q}''_w(x,t)$ are computed; then the temperature distribution in the solid is computed to obtain the surface temperature distribution in the solid is computed to obtain the surface temperature distribution; finally the new xp is determined based on the condition $T = T_{ig}$ at the surface. The computation is started at the instant the burner is placed near the bottom of the wall. Equations are solved using a finite differential numerical procedure. Because of stiff temperature gradients close to the surface, a nonuniform grid is used with a higher grid density near the surface.

EXPERIMENTS

Experiments were conducted on a small but turbulent scale apparatus which allowed testing of 30 cm wide × 120 cm high samples. Measurements of the turbulent flame height and pyrolysis height as a function of time were made for various practical materials. Sample were flush mounted in a larger backboard of inert material to ensure a two-dimensional flames as much as possible and to maintain a continuous flame wall over the sample height. Distance from the leading edge of the sample was marked on the surrounding walls to measure flame height and pyrolysis height. A high shutter-speed video camera was used to record the flame propagation process and to measure flame height and pyrolysis height at various stages of spread. Additional details on the experimental setup, instrumentation, and test procedure are given by[10].

DISCUSSION AND RESULTS

Model calculations and experimental data for flame spread are presented in Figure 3 through 6 for 3.2 mm thick hardboard, 12.7 mm thick plywood and material X. Hardboard is a relatively homogeneous wood-based material, plywood is made of laminated wood bonded by adhesive, and material X is a fiberglass matrix embedded in epoxy. Flame height was based on the top most visible tip of the flame from a single frame of video. Sporadic, detached flamelets less than 5 cm in size were ignored. Ten consecutive frames were read at the beginning of each time step and the average flame height and fluctuations were determined.

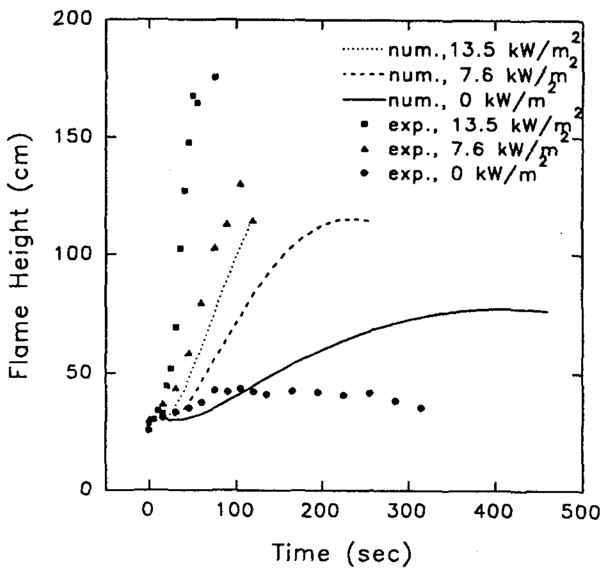

Fig. 3. Flame height comparison for plywood.

The same technique was applied to all flame height measurements. The pyrolysis height was the most difficult to measure. A researcher with a side view of the burning simple held a painted pointer to locate the pyrolysis height. Although flames may spread above the height of the sample, flame spread was not classified as sustained unless the pyrolysis front also spread to the top of the sample.

Some of the properties were measured in the laboratory(ρ and $\dot{q}''_{f0}$) and others (h_c, c, k, and T_{ig}) were obtained from literature[8,14-17]. The range of values found for the combination of properties called thermal inertia ($k\rho c$) spanned an order of magnitude. k and c for wood based materials are known to vary with moisture content and temperature, which may account for some of the variation of the thermal inertia values found in literature.

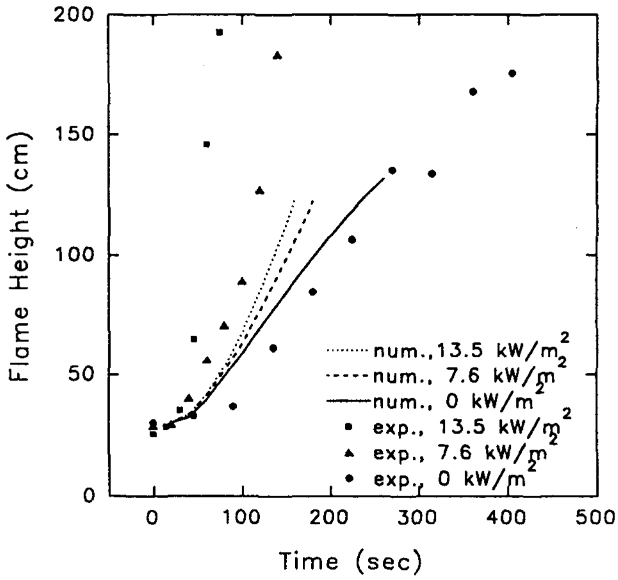

Fig. 4. Flame height comparison for hardboard.

In Fig. 3, the numerical predictions for flame height on 12.7mm thick plywood are shown for three different levels of external radiation, the experimental flame heights are denoted with symbols while lines are used for the numerically determined flame heights. Without the application of external radiation, the experimental flame spread was not sustained to the top of the sample (height of sample was 120 cm). It did not spread above 50 cm. The numerical prediction also showed a slow flame spread rate and after 450 seconds, the flames had reached about 75 cm, about the experimental value. At external radiation levels of 7.6 kw/m^2 the flame spread was again not sustained to the top of the sample. The numerical model predicted this result but consistently under predicted the flame height. For the highest level of external radiation (13.5 kw/m^2), the numerical predictions showed sustained spread to the top of the sample, which corresponded to the experimental results. The primary reasons for the difference between the predictions and the data may be attributed to the lack of accurate property data, as described later.

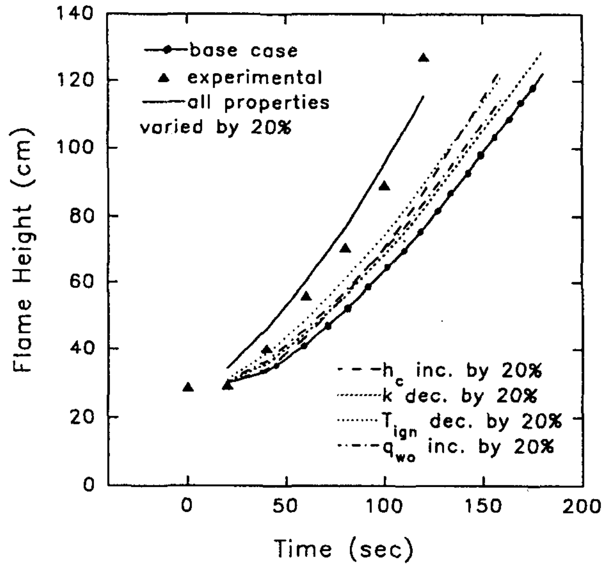

Fig. 5. Sensitivity of model predictions of flame height.

Flame spread heights as a function of time are shown for 3.2 mm thick hardboard in Fig. 4. In this set of experimental tests, flames spread to the top of the sample for all levels of external radiation. Without external radiation, the flame spread height was predicted fairly accurately; but for the higher levels of the external radiation, the flame height was consistently under predicted. Selection of property data posed some difficulties as was previously discussed. To investigate the sensitivity of the upward flame spread model to property data, several properties of the hardboard were changed, each by twenty percent. The results are shown in Figure 5. h_c and $\dot{q}''_{f0}$ were increased by twenty percent of values used in the base case. As anticipated, flame spread increased. k was then decreased by twenty percent. This lower thermal conductivity caused increased flame spread because the heat flux applied at the surface did not conduct into the thermal, there by causing the surface to heat faster. Decreasing T_{ig} also increased flame spread since the sample requires less energy input to heat to its ignition temperature. It was shown recently [17] that the T_{ig} for PMMA may be as low as 329°C, as opposed to the widely accepted value of around 370°C. The flame height for each of the changes is shown in Fig. 6. If all four properties were varied, the numerically determined flame height over predicted the experimental flame height.

The model was run independently by another group of researchers [18] for a composite material (made of epoxy and fiberglass) and compared with their data. The material properties were measured for the specific material, not obtained from literature. Results for the material are shown in Fig. 6. The two curves represents two different correlations for flame heat feedback in the model and the bars indicated fluctuations in the data. The results show very good agreement between experimental measurement and prediction of flame height. This confirms the robustness of the model and suggests that property data obtained for exactly the same type of material may be needed for the accurate prediction of flame spread rates.

CONCLUSIONS

In the current model, emphasis has been placed on developing a practical model that will be useful for a broad range of materials and may be part of a large room fire model. Some of the important aspects of the model are: the addition of external radiation to simulate a wall that is part of an enclosure fire and has flaming walls radiating to it, the use of a correlation for flame heat feedback distribution to the sample surface based on data available in the literature, and the use of an experimentally measured mass loss rate for the sample material. The development of the mathematical model is presented and flame spread predictions obtained using the model are compared with experimental results. For the material tested, the model does a reasonable job of predicting flame spread. In order to obtain better predictions, the current

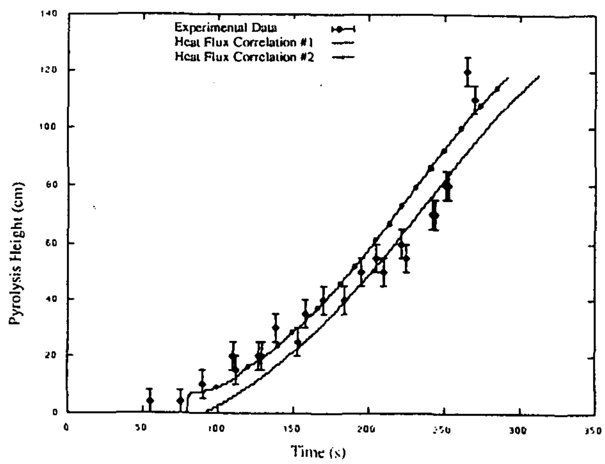

Fig. 6. Pyrolysis height comparison using present model by Ohlemiller and Cleary.

work suggests a need for thermal property data for practical materials that will be appropriate for flame spread models.

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