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Significant Parameters for Predicting Flame Spread

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TABLE OF CONTENTS

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Summary

Flame spread is considered on a vertical wall surface in a vented enclosure. A theoretical formulation is developed to describe the burning and fire spread behavior and its response to the changing environmental conditions of the room. These formulations have been kept simple in form, but consistent with current levels of accuracy and completeness. The primary aim was to establish the relevant and significant set of dimensionless parameters which govern the fire spread process. These are given in terms of room geometric factors and wall flammability properties. No solution of the equations has been developed.

Introduction

The flammability of interior surface lining materials has received much attention in the development of test methods used for hazard classification and in the development of its basic understanding through research studies. The former development produces relative hazard levels based on measurements and judgement. The latter development offers the prospect of prediction of flame spread based on material property data and mathematical analysis. Yet with the versatility of such a predictive methodology comes imprecision in application techniques. Accordingly the introduction of many variables from the predictive equations will present problems for decision-makers. Thus it is necessary to simplify the analysis without ignoring the significant processes of the problem, maintain a useful level of accuracy, and identify measurable properties (data) to characterize the materials.

In this study, a set of governing equations is presented. The equations describe the enclosure environmental conditions -- room temperature, T; oxygen concentration, Y_{ox}; and the flame spread behavior for a wall of the enclosure. Some idealizations will be made, but they should not significantly alter the characteristics of the problem. Indeed, no solution will be developed; however, the resulting set of independent dimensionless variables will be developed. These dimensionless groups could be useful in developing experimental correlations, highlighting important properties, and perhaps ultimately simplifying hazard assessment. But no conclusions will be made on these possible benefits at this time.

Theory

Several assumptions will be made at the outset to lay some concepts for the model. As each of these assumptions are relaxed, of course the analysis would change. Nevertheless, it is felt these changes would only be in detail, not in substance. These assumptions are given below:

(1) The enclosure surface members are considered to be infinite in thickness with respect to heat conduction phenomena, and of uniform thermal properties;

(2) The enclosure interior surface temperature is considered to be uniform at any time.

(3) Fire originates on a wall which is the only combustible element in the enclosure except for a line-source ignition fire.

(4) The wall fire burns by a simple vaporization process, and its pyrolysis region is a rectangle (i.e., spread along the ceiling jet region is considered by an equivalent but fictitious vertical spread region and upward spread is more rapid than side or lateral spread).

The specific problem addressed is illustrated in Figure 1. The enclosure has one vent — a window in this case — but several wall vents could be considered. The rear wall is ignited by a line burner of energy release rate $\dot{E}_o$; this is assumed to be fixed over time in this example. Its width, $2x_{p,o}$ determines the initial wall pyrolysis width after ignition; the height of the pyrolysis zone being given by y_p, and its burn-out front given by y_b. Because vertical spread is assumed much faster than lateral spread the pyrolysis region is always approximately rectangular. Also as the pyrolysis front reaches the ceiling $(y_p = H)$, the horizontal spread along the ceiling is considered similar to upward spread since both depend on the same buoyancy generated flow and any subsequent downward propagation from the ceiling is considered the same as lateral spread to the side. Hence we ignore the complexities of the flame front boundary on the wall, and need only be concerned about the extent of the combustible rectangular region. This concept is also consistent with the assumption of a uniform compartment surface temperature.

A brief sketch of the equations will be given. The gas temperature T in the upper region of a compartment due to a fire energy release rate $\dot{E}$ can be given as[1]

$$T = T_o \left\{ 1 + C_T \left(\frac{\dot{E}}{\rho_o T_o c_p \sqrt{g}\, A_o \sqrt{H_o}} \right)^{2/3} \left(\frac{h_w A_w}{\rho_o c_p \sqrt{g}\, A_o \sqrt{H_o}} \right)^{-1/3} \right\} \qquad (1)$$

where $C_T = 1.63$, $T_o = 295$ K, A_w is the interior enclosure surface area and A_o is the vent area with ρ_o and c_p the ambient gas properties. A thermal conductance h_w is given for an infinitely thick wall as $\sqrt{k\rho c/t}$ with $k\rho c$ the enclosure properties, and t is time. The energy release rate is considered composed of the ignitor and the pyrolyzing wall. The wall pyrolysis rate per unit area is approximated as[2]

$$\dot{m}'' = \frac{h}{c_p} \ln(1+B) \approx \frac{h}{c_p} B \qquad (2)$$

where the "Spalding" B-number includes surface and flame radiative effects in terms of a radiation fraction of total energy release,

χ_r; compartment radiation flux, $\dot{q}''_e \approx \sigma T^4$; and surface radiative loss, σT_{ig}^4 with T_{ig} the vaporization temperature. The B-number is defined as follows:

$$B = \left(\frac{1}{1 + \frac{1}{2} \chi_r \Delta H/L}\right) \left\{ B_o \zeta_{ox} - \left(\frac{c_p T_{ig}}{L}\right) \left[(1-\phi) + \frac{\sigma T_{ig}^3}{h} \left(1-\phi^4\right) \right] \right\} \qquad (3)$$

where ΔH is heat of reaction, L is heat of vaporization, $\zeta_{ox} = Y_{ox}/0.233$ the normalized oxygen mass fraction in the enclosure, $\phi = T/T_{ig}$ the normalized enclosure gas temperature, and h is the convective transfer coefficient given by

$$\frac{hH}{k} = C_h \,(Gr\,Pr)^{1/3} \qquad (4)$$

which applies to turbulent natural convection conditions -- the Grashof number $Gr = g\left(1-\phi_o\right)H^3/\nu^2$ and Prandtl number $Pr = \rho\nu c_p/k$ with $\phi_o = T_o/T_{ig}$ and H the enclosure height. It should be noted that h is approximately constant for these conditions, and it will be thus regarded as such. Also, a nominal convective B number is

$$B_o = 0.233\ \Delta H_{ox}\ \left(1 - \chi_r\right)/L = 0.233 \left(\frac{\Delta H}{L}\right) \left(\frac{1 - \chi_r}{\gamma}\right) \qquad (5)$$

with the heat of reaction per unit mass of oxygen, $\Delta H_{ox} = \Delta H/\gamma$, and γ is the stoichiometric oxygen to fuel mass ratio.

Hence the energy release rate is given as

$$\dot{E} = \begin{cases} \dot{E}_o, & t < t_{ig} \\ \dot{E}_o + \dot{m}''A_p, & t \geq t_{ig} \end{cases} \qquad (6)$$

where A_p is the pyrolysis area and t_{ig} is the time to ignite the wall by $\dot{E}_o$. The ignition time can be given by

$$t_{ig} = \frac{\pi}{4} k\rho c \left[\left(T_{ig} - T_o\right)/\dot{q}''_o\right]^2 \qquad (7)$$

where $\dot{q}''_o$ is the incident exposure flux by $\dot{E}_o$ roughly 2 to 3 W/cm^2 due to a moderate size flame (~ 1 m).[4] But if $\dot{q}''_o$ is less than σT_{ig}^4 the material will not ignite since the loss at pyrolysis is greater than the heat supplied.

The pyrolysis area A_p following ignition is given by $2x_p\left(y_p - y_b\right)$ with initial values at $t = t_{ig}$ determined by the width and height of the $\dot{E}_o$ flame: i.e. $x_{p,o}$ and $y_{p,o}$. In dimensionless terms, $\alpha = A_p/2x_{p,o}y_{p,o}$ is given by

$$\alpha = \left(\eta_p - \eta_b\right) \xi_p \qquad (8)$$

where $\eta_{p,b} = y_{p,b}/y_{p,o}$ are the respective pyrolysis and burnout fronts, respectively, and ξ_p is the lateral pyrolysis position, $x_p/x_{p,o}$.

The upward pyrolysis front can be found from[5]

$$\frac{d\eta_p}{d\tau} = \frac{\eta_f - \eta_p}{\tau_f} \tag{9}$$

where $\tau = t/t_f^*$ and $\tau_f = t_f/t_f^* = \{(1-\phi_s)/[\mu(1-\phi_o)]\}^2$ and t_f^* is a normalizing time variable associated with upward spread time, and is given as $k\rho c\ [c_p(T_{ig} - T_o)/(hB_oL)]^2$.

The dimensionless flame height is given by[4]

$$\eta_f = \eta_b + \left[1 + \frac{\mu(\eta_p - \eta_b)}{\zeta_{ox}} C_f B_o \pi_4\right]^{2/3} \tag{10}$$

where C_f is a constant and $\mu = B/B_o$. The initial condition is $\tau = \tau_{ig}$: $\eta_p = 1$, $\eta_b = 0$.

The burnout front can be estimated from the following equation[5],

$$\frac{d\eta_b}{d\tau} = \frac{\eta_p - \eta_b}{\tau_b} \tag{11}$$

where $\tau_b = t_b/t_f^*$ and the burn time $t_b = m''/\dot{m}''$, m'' being the consumable mass per unit area available. The initial condition is $\tau = \tau_{ig} + \tau_{b,o}$ (where $\tau_{b,o}$ is evaluated at τ_{ig}) and $\eta_b = 1$.

The lateral spread rate is given by[4]

$$\frac{d\xi_p}{d\tau} = \left[\frac{\Phi_o}{x_{p,o}(hT_{ig})^2}\right] \left[\left(\frac{c_p T_{ig}}{L}\right)\left(\frac{\zeta_{ox}}{B_o}\right)\left(\frac{1 - \phi_o}{1 - \phi_s}\right)\right]^2 \tag{12}$$

where Φ_o is a flame heating parameter measured under normal air conditions as given in ref. 3.

The enclosure surface temperature was estimated by considering the net radiative and convective enclosure heat transfer from T to T_s (the surface temperature) as equal to the heat transfer rate from the gas into the enclosure to a sink at T_o. As a consequence it can be shown that

$$\frac{\phi_s - \phi_o}{\phi - \phi_o} = \frac{1}{1 + \dfrac{h_w}{h + h_r}} \tag{13}$$

where h_r is a radiative gas-surface exchange coefficient which depends primarily on those corresponding temperatures. As an approximation let h_r be represented as σT^3 where emissivities, geometry and surface temperatures have been ignored. Thus h_r/h can be represented as $\phi^3(\sigma T_{ig}^3/h)$.

Finally, the enclosure oxygen concentration can be estimated by a specie mass balance

$$Y_{ox} = 0.233 - \dot{E}/\left(\dot{m}_o \, \Delta H_{ox}\right) \tag{14}$$

in which the vent mass flow rate was taken as

$$\dot{m}_o = \frac{2}{3} C_o \, A_o \, \sqrt{H_o} \, \rho_o \, \sqrt{2g\left(\frac{T_o}{T}\right)\left(1 - T_o/T\right)} \, \left(1 - \frac{N}{H_o}\right)^{3/2} \tag{15}$$

with N/H_o taken as 1/2.

Combining eqns. (14) and (15) and making variables dimensionless leads to

$$\zeta_{ox} = 1 - \left\{ \frac{3}{C_o} \pi_1 \left(\frac{c_p T_{ig}}{L}\right)\left(\frac{L}{\Delta H}\right) \gamma \phi_o / \sqrt{\left(\frac{\phi_o}{\phi}\right)\left(1 - \frac{\phi_o}{\phi}\right)} \right\} \cdot \left\{1 + \mu \alpha C_f B_o \pi_4\right\} \tag{16}$$

The dimensionless equation for temperature corresponding to eq. (1) can be given as

$$\frac{\phi - \phi_o}{\phi_o} = C_T \, \left(\pi_1 \psi\right)^{2/3} \, \left[B_o \pi_2 / \sqrt{\tau}\right]^{-1/3} \tag{17}$$

with ψ the dimensionless energy release rate $\dot{E}/\dot{E}_o$ given as

$$\psi = \begin{cases} 1, & \tau \leq \tau_{ig} \\ 1 + \mu \alpha C_f B_o \pi_4, & \tau \geq \tau_{ig} \end{cases} \tag{18}$$

Also the initial pyrolysis height, taken to correspond to the flame height caused by $\dot{E}_o$ can be found from eq. (10).

$$\frac{y_{p,o}}{x_{p,o}} = \frac{\pi_1}{\pi_2}\left(\frac{A_w}{2x_{p,o}^2}\right)\left(\frac{c_p T_o}{\Delta H}\right) . \tag{19}$$

From these equations the following independent dimensionless groups can be identified and interpreted. These are listed below:

$$\pi_1 = \frac{\dot{E}_o}{c_p T_o \rho_o \sqrt{g} \, A_o \, \sqrt{H_o}} \text{, ignition energy/vent enthalpy}$$

$$\pi_2 = \frac{hA_w}{\rho_o c_p \sqrt{g}\, A_o \sqrt{H_o}}, \quad \frac{\text{enclosure heat loss}}{\text{vent enthalpy flow}}$$

$$\pi_3 = \hat{\gamma}, \quad \frac{\text{mass of oxygen required}}{\text{mass of fuel pyrolyzed}}$$

$$\pi_4 = \frac{\gamma h}{c_p}\left(\frac{2\, c_p T_o x_{p,o}}{\rho_o^2\, g\, (1-\chi_r)\, \dot{E}_o}\right)^{1/3}, \quad \frac{\text{oxygen required in combustion}}{\text{induced air supply}}$$

$$\pi_5 = \frac{c_p T_{ig}}{L}, \quad \frac{\text{ignition energy}}{\text{vaporization energy}}$$

$$\pi_6 = \frac{\sigma T_{ig}^3}{h}, \quad \frac{\text{radiative heat loss}}{\text{convective heat loss}}$$

$$\pi_7 = Gr = \frac{g(1 - \phi_o)\, H^3}{\nu^2}, \quad \frac{\text{buoyant force}}{\text{viscous force}}$$

$$\pi_8 = Pr = \frac{\rho \nu c_p}{k}, \quad \frac{\text{viscous effect}}{\text{thermal conduction effect}}$$

$$\pi_9 = \frac{\sigma T_{ig}^4}{\dot{q}''_o}, \quad \frac{\text{radiative heat loss}}{\text{applied ignitor heat}}$$

$$\pi_{10} = \frac{m''}{(k\rho c/hc_p)}, \quad \frac{\text{burnable mass}}{\text{heated mass}}$$

$$\pi_{11} = \frac{\Phi_o}{x_{p,o}\,(hT_{ig})^2}, \quad \frac{\text{flame heat transfer in opposed flow}}{\text{energy required for spread}}$$

$$\pi_{12} = \chi_r, \quad \frac{\text{flame energy radiated}}{\text{total flame energy}}$$

$$\pi_{13} = T_{ig}/T_o, \ \frac{\text{ignition temperature}}{\text{initial temperature}}$$

$$\pi_{14} = \frac{\Delta H}{L}, \ \frac{\text{combustion energy}}{\text{vaporization energy}}$$

$$\pi_{15} = \frac{hH}{k}, \ \frac{\text{convective heat}}{\text{conductive heat}}$$

$$\pi_{16} = \frac{A_w}{x_{p,o}^2}, \ \frac{\text{interior surface area}}{\text{initial pyrolysis area}}$$

The above dimensionless groups govern the problem and must be accounted for by measured data. The next step is to evaluate their significance in terms of their variability and sensitivity with respect to a solution of the equations.

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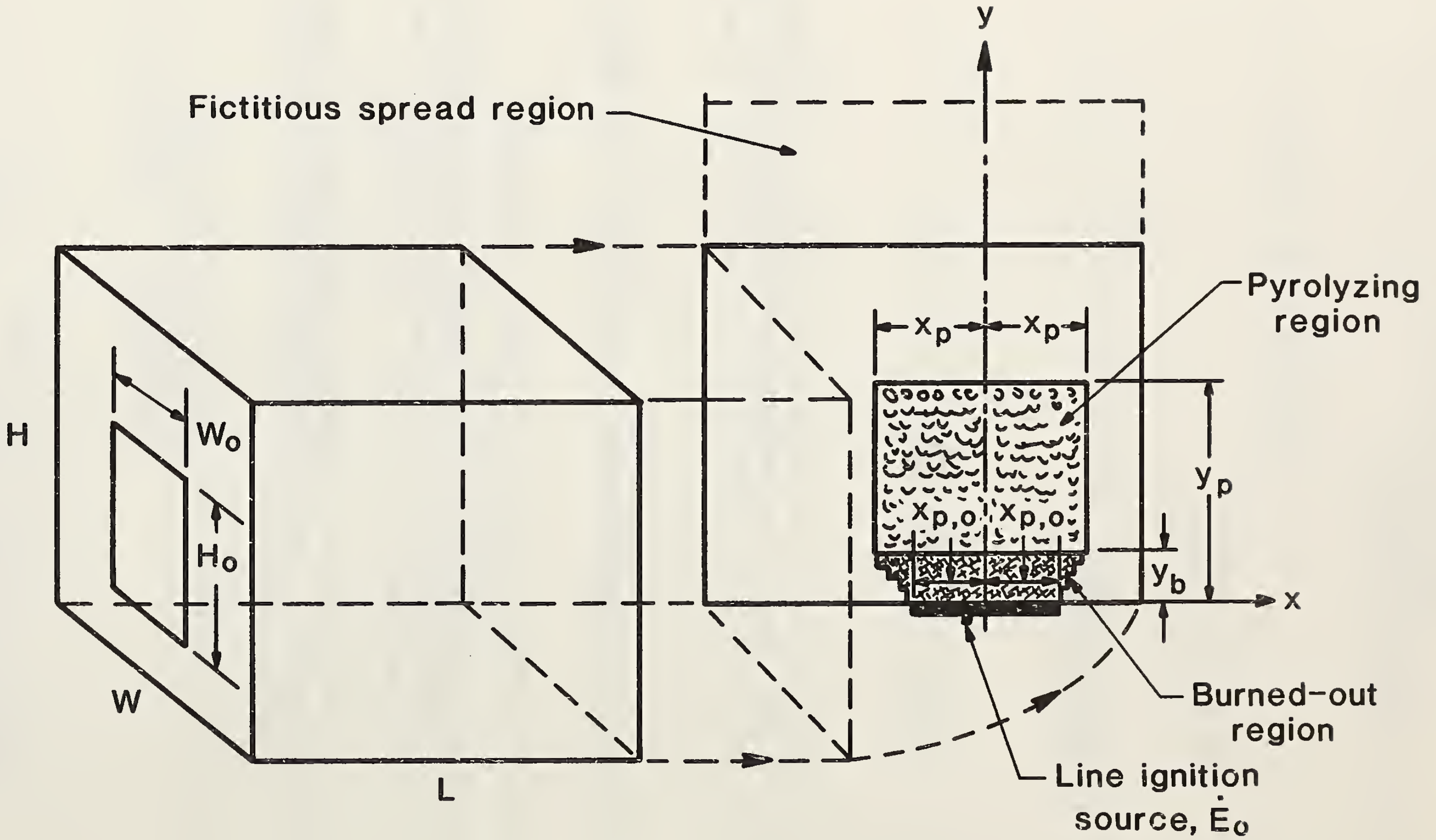

Figure 1. Enclosure Wall Fire Spread

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Flame spread is considered on a vertical wall surface in a vented enclosure. A theoretical formulation is developed to describe the burning and fire spread behavior and its response to the changing environmental conditions of the room. These formulations have been kept simple in form, but consistent with current levels of accuracy and completeness. The primary aim was to establish the relevant and significant set of dimensionless parameters which govern the fire spread process. These are given in terms of room geometric factors and wall flammability properties. No solution of the equations has been developed.

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