SPONTANEOUS IGNITION OF SOLIDS SUBJECTED TO LINEARLY TIME-DEPENDENT RADIANT EXPOSURE

by

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ABSTRACT

The important problem of spontaneous ignition of solids heated by temporarily variant thermal radiant exposure is studied. Available data are examined in the light of a simple heat balance analysis to find that the observed behavior is predictable. An exposition of the elements of this general problem of ignition is made to realize that further research is required to predict the ignition behavior of realistic solids under realistic reradiative and free convective loss conditions.

INTRODUCTION

Little, if any, quantitative knowledge exists about the important problem of the spontaneous ignition response of a combustible solid subjected to time-wise ramped thermal radiative exposure. Martin (1) developed some preliminary experimental data by exposing blocks of wood to a transiently varying radiant flux. In one set of data (2), the source of radiation is a model room compartment in which a propane burner, remote from the target, continuously pumps combustive energy to transiently heat the room which then radiates to the target. The radiant flux in this set up varies with time in the early phases, more or less linearly, in the range of $r = 10^{-2}$ -10^{-1} W/cm^{2}s. In the second set of data, the source of radiation is an electrically powered heater which is manually programmed to yield flux rate ramps in the range $r = 10^{-1}$ -10^{0} W/cm^{2}s. In both these test series , the time to ignition t_{ig} of the wood block is noted as a function of the exposure flux rate.

These data are presented in Fig. 1. The time to ignition is noted to decrease with increasing flux rate according to

$$t_{ig,exptl} \approx 17.6\ r^{-2/3} \tag{1}$$

where time is in seconds and ramp rate is in W/cm^{2}s. Also presented in Fig. 1 are the same data but manipulated to obtain the flux at ignition (rt_{ig})(W/cm^2) as dependent on the rate of heating rate r. If it were not for the dynamics of the heating and ignition processes , one expects this critical flux to be independent of the ramp rate r. The data, however, show that ignition occurs at a lower flux when the ramp rate is low, approximately according to $rt_{ig} = 17.6\ r^{1/3}$.

The question addressed in this paper is this: Is it possible to predict, from a theoretical basis, the constant of proportionality and the power 2/3 appearing in Eq. (1) as

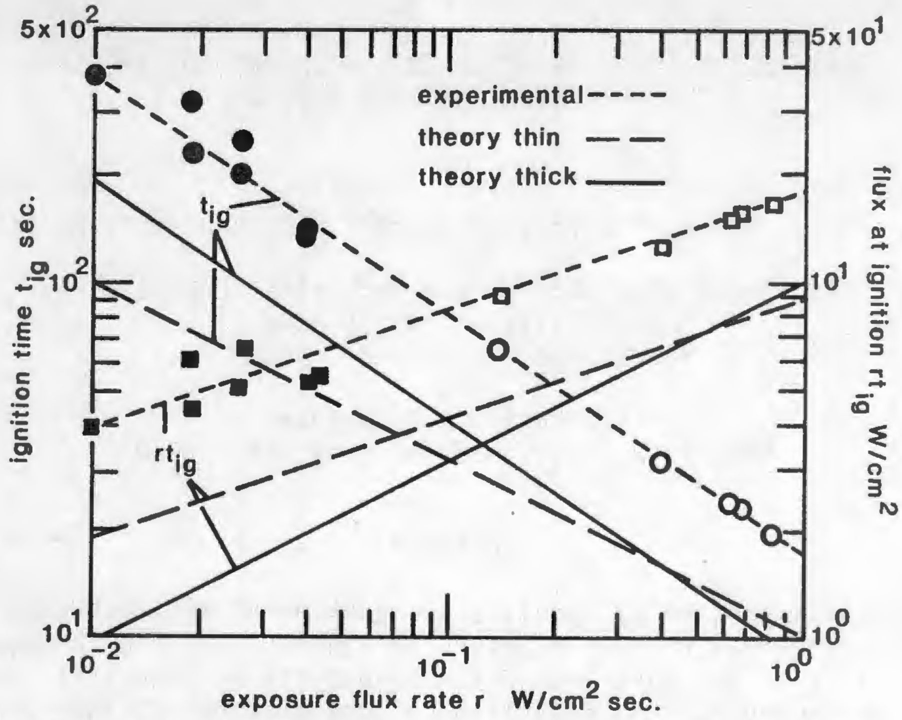

Figure 1: Ignition Time●○ and Flux at Ignition■□ as Dependent on the Exposure Flux Rate.
Open Symbols Data from (1).
Filled Symbols Data from (2).

dependent upon the various thermal and physical properties of the system?

ANALYSIS

Thin Slab:

Consider a target of thickness ℓ, conductivity K_s, density ρ_s, specific heat C_s and initial temperature T_i exposed for time t equal to and greater than zero to a heat flux (W/cm^2) ramped linearly as $j=j_o+rt$, where the ramp rate r has units of flux per unit time, i.e., W/cm^2 sec.

If the target is thermally thin, its temperature will be uniform throughout its thickness. This time-dependent temperature $T_s(t)$ is given by an energy balance.

$$\rho_s C_s \ell \,(T_s - T_i) = a_s \int_0^t (j_o + rt)dt + \text{losses} \qquad (2)$$

The left hand side represents the increase in energy content of the solid whose volume per unit surface area is ℓ. The integral in the first term on right hand side is the amount of energy arriving at the surface in time t; a fraction a_s of this is absorbed by the surface, a_s being an absorptivity constant. There are four types of 'losses' to be considered. Losses from the backface of the slab are absent if it is perfectly insulated. As the solid becomes warmer, the front face begins to transiently reradiate to its surroundings. It also experiences a transient natural convection process by which further energy is lost. Additionally, the pyrolysis of the solid to produce combustible gases may involve an energy sink. All these four types of losses are ignored in the present work. Parenthetically, it is important to note that the very same transient free convection process which tends to slow down the heating of the solid also brings into the boundary layer the oxygen required for oxidation of the pyrolyzates to eventually culminate in a flame. Equation (2), integrated under these simplifications, leads to

$$\rho_s c_s \ell (T_s - T_i) = a_s (j_o + rt/2)t \quad (3)$$

If attainment of a critical temperature $T_s = T_{ig}$ is taken as the criterion for ignition, the ignition time is obtained from from Eq. (3) by simply setting $t = t_{ig}$ when $T_s = T_{ig}$. Since flux ramps generally start with $j_o = 0$,

$$t_{ig,thin} = \{2\rho_s C_s \ell (T_{ig} - T_i)/a_s\}^{1/2} r^{-1/2} \quad (4)$$

Thick Slab:

If the slab considered above were thermally thick, internal spatial temperature gradients exist. As heating progresses, progressively thicker will be the heated layer of the solid near the exposed surface. This thermal layer thickness δ_s: (a) delineates the depth beyond which stations within the solid do not know that the surface is experiencing heating;(b) determines the characteristic temperature gradient in the solid; and (c) determines the rate at which the solid energy content increases. Taking temperature to vary linearly within the solid from T_s at the surface to T_i at the depth δ_s from the surface, the time-dependencies of the surface temperature T_s and the thermal penetration depth δ_s are coupled by

$$K_s (T_s - T_i)/\delta_s = a_s (j_o + rt) \quad (5)$$

Ignoring all the losses as in the case of thin slab, the energy conservation is given, with the linear temperature distribution within the solid, by

$$\rho_s c_s (T_s - T_i)\, \delta_s/2 = a_s (j_o + rt/2)t \quad (6)$$

Assuming $j_o = 0$, resolution of Eqs. (5) and (6) for δ_s and T_s leads to $\delta_s = \surd(K_s t/\rho_s c_s)$ and $(T_s - T_i) = \surd(a_s^2 r^2 t^3/K_s \rho_s c_s)$. With the critical temperature criterion, ignition time is thus given by

$$t_{ig,thick} = \{K_s \rho_s C_s (T_{ig} - T_i)^2/a_s^2\}^{1/3} r^{-2/3} \quad (7)$$

DISCUSSION AND CONCLUSIONS

Taking wood properties to be those of typical fir, $\rho_s \approx 600$ kg/m^3, $C_s \approx 2720$ J/kg K and $K_s \approx 0.12$ W/mK, and taking ignition temperature to be about 900 K and the typical thin sample thickness to be 5×10^{-4}m with $a_s = 1$, Eqs. (4) and (7) can be reduced to

$$t_{ig,thin} = 9.9\, r^{-1/2} \quad (4a)$$

$$t_{ig,thick} = 8.9\, r^{-2/3} \quad (7a)$$

where, as in Eq. (1), the time is in seconds and ramp rate is in W/cm^{2}s. These results are also shown in Fig. 1.

Both thin and thick body models predict the trend of shorter the ignition time at larger ramp rate. Even more interestingly, the thick body model successfully predicts the observed inverse 2/3-power dependence of ignition time on ramp rate. While the trend and sensitivity are thus captured by the thick body analysis, the predicted ignition time is consistently about half the measured. An absorptivity of 0.5 would raise the constant 8.9 in Eq. (7a) to 14.1, still underpredicting by about 20%. Variations in the thermal properties can perhaps account for this discrepancy.

Even more importantly, the assumed linear temperature profile in the solid inherently tends to underestimate δ_s and (T_s-T_i) at any given time. Thus a more rigorous solution of the conduction problem is expected to result in a shorter time to ignition under a given set of conditions. Pyrolysis endothermicity, and heat losses by radiation and natural convection point towards a longer time to ignition. The magnitudes of these improvements, however, can not be estimated without obtaining a complete solution.

It is surprising that the thick body behavior is retained over the relatively wide range of the tested ramp rate. Conceptually, one would expect that low heat fluxes and flux rates make even thick solids behave as thin. The r value representative of this transition from thick to thin solid behavior is apparently smaller than 10^{-2} W/cm^{2}s.

The present agreement between thick body analysis and experiment is quite fortuitous. There is no assurance that this agreement will persist for taller and shorter target slabs and for larger or smaller ramp rates. This pessimism is not without reason. The development of thermal reradiation from the heated surface, evolution of the natural convection boundary layer adjacent to the surface, pyrolysis of the solid, mixing, of the pyrolyzates with air in the boundary layer and the thermal runaway of the mixture, are all highly transient but essential aspects of the problem. The simple result given by Eqs. (4a) and (7a) can not be expected to be so versatile as to capture the extreme nonlinearities involved in the total transient problem. In fact, such crucial phenomena as critical heating below which ignition is impossible can not be predicted without accounting for at least some of these enumerated transient aspects. In (3), for instance, the authors have developed a model for the transient heating of thin vertical slabs by constant radiant flux to discover some important quirks of the boundary layer development and heat loss from the surface. A threshold heat flux (dependent upon the solid height as well as the reradiant loss), below which ignition is impossible, has been determined in this reference.

Other aspects of the total problem of spontaneous ignition of solids subjected to time-wise varying exposure radiant flux are currently being investigated.

REFERENCES

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