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A methodology for the estimation of ignition delay times in forest fire modelling

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ABSTRACT

A methodology for the estimation of ignition times on solid materials is presented. It is based on the observation that the time to ignition is proportional to the squared time integral of the incident heat flux. This relationship can be readily demonstrated for the classical solutions for time to ignition which consider constant incident heat fluxes. Thus, ignition times can be calculated only with the knowledge of the incident heat flux on the sample (gas-phase calculations) and experimental ignition results. This method is particularly useful when modelling wildfire propagation, where grid resolution is larger than some solid objects. Analytical solutions of the transient conduction problem for constant and ramping incident heat fluxes are discussed. The proportionality between the time to ignition and the squared integral of the incident heat flux was verified experimentally for constant and time-varying incident heat fluxes, showing that the proposed methodology can be applied to both cases. The methodology is outlined and an example is presented.

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1. Introduction

The prediction of flaming ignition of solid fuels is necessary in many fire safety applications. Flaming ignition is the result of a series of phenomena occurring simultaneously in the gas and solid phases that could imply great modelling complexity [1]. In cases such as the prediction of compartment fire growth, detailed resolution of the coupled solid and gas phase processes is necessary [2,3] and the main challenge is to establish the model input parameters [4]. In the case of forest fire propagation, where atmospheric type models are used, the gas phase grid resolution is of the order of several meters [5,6]. Since the characteristic dimensions of the combustible materials like trees or building elements are smaller than the grid size, predicting material ignition becomes computationally burdensome as the solid phases require a more refined grid. It would therefore be convenient to decouple the gas and solid phases so that ignition can be predicted without the need to resolve the solid phase, and only on the basis of gas phase calculations and experimental results.

A problem of great importance where solid and gas phase interaction is most effectively treated by the decoupling of both phases is the occurrence of fires within the Wildland–Urban Interface (WUI). Major WUI fires have been reported in several countries [7] and an overview of this problem has been presented by Rehm [8]. Here, forest fires interact with buildings, redefining fire propagation. It is therefore important to understand the interaction between wildfires and building materials. The two main scenarios are building material ignition through transport of fire brands and propagation via direct action of flames on buildings. The former case has been discussed by Manzello et al. [7] while latter case will be the subject of this study.

This article presents a methodology for predicting the flaming ignition of thermally thick building materials exposed to radiant heat fluxes caused by an approaching flame front. The proposed method eliminates the need to perform solid phase calculations: ignition times are obtained as a function of the incident heat flux to the solid fuel surface and piloted ignition test results. Classical solutions to the flaming ignition problem as well as solutions for time-varying incident heat fluxes are discussed. The method is validated using experimental data for time-varying and constant incident heat fluxes. An example of the methodology is provided and its limitations are discussed.

2. Definition of the problem

Due to the high intensities of the heat fluxes caused by some wildfires, radiant ignition of objects located at the order of tens of meters away from the fire front can be achieved [9]. An approaching fire imposes a time-varying heat flux on a stationary target [7,9]. The shape of the heat flux-time curve is variable (Fig. 1). However, it can generally be split into a long preheat period (due to long distance radiative exposure), where the incident heat flux will lead to equilibrium temperatures far below those required for ignition, and a short ramp where the heat flux

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Nomenclature

c_p	specific heat (J kg^{-1} K^{-1})
h	convective heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
$\dot{q}''_{ext}$	incident heat flux on the solid surface (kW m^{-2})
$\dot{q}''_{net}$	net heat flux on the solid surface (kW m^{-2})
m	slope of the ramping incident heat flux (kW m^{-2} s^{-1})
T	temperature (K)
t_{exp}	sample exposure time to the incident heat flux (s)
t_{ig}	ignition delay time (s)
t^c_{ig}	computed ignition delay time (s)
t_p	pyrolysis time (s)

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
ρ	density (kg m^{-3})
θ	temperature difference (K)
θ_r	reference temperature (K)

Subscripts

∞	infinity, ambient
ig	ignition

increases rapidly. In order to establish fire spread at the WUI, it is necessary to predict ignition delay times of building materials subjected to time-varying heat fluxes of this kind. Given the required accuracy associated to this particular problem, these time-varying heat fluxes can be approximated as linear functions of time. For the purposes of this work, the preheat period will be neglected and the curves shown in Fig. 1 will be approximated as an growing linear ramp starting at a baseline heat flux.

Flaming ignition is controlled by two mechanisms, the heating and pyrolysis of the solid fuel and the gas-phase chemical reactions. For conditions when the gas-phase induction times are short, characterized by low flow velocities with normal oxygen concentrations, the ignition delay times become close to the heating and pyrolysis times. In these cases, ignition is controlled by the heat transfer to the solid [10]. Classical approaches to the flaming ignition problem [11,12] consequently only model the heating of an inert solid, obtaining analytical solutions to the one-dimensional heat diffusion equation under several assumptions. By considering an arbitrary ignition temperature at the surface (typically assumed to be equal to the pyrolysis temperature), times to ignition are calculated. The applicability and limitations of this approach have been discussed by several authors [1,10,13–16].

Considering a one-dimensional, semi-infinite, inert solid subjected to an incident radiative heat flux and convective heat losses at the exposed surface, the heat diffusion equation is expressed as

$$\frac{\partial^2\theta(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial\theta(x,t)}{\partial t}, \tag{1}$$

with $\theta(x,t) = T(x,t) - T_\infty$. The boundary and initial conditions are given by

$$\begin{aligned} &\dot{q}''_{net}(t) = \dot{q}''_{ext}(t) - h\theta(x,t) = -k\frac{\partial\theta(x,t)}{\partial x}, \quad x = 0;\\ &\theta(x,t) = 0, \quad x \to \infty;\\ &\theta(x,0) = 0, \quad \forall x. \end{aligned} \tag{2}$$

The convective heat transfer coefficient h can incorporate both convective and radiative losses following standard techniques. This formulation represents the thermally thick limit for the solid fuel heating problem. The present work will not deal with the thermally thin limit, as in most practical situations the building materials will behave as thermally thick solids [10].

3. Solutions for solid fuel ignition

3.1. Solution for a constant incident heat flux with surface losses

Classical ignition modelling uses an analytical solution for the surface temperature for the case of a constant incident heat flux to the surface [17,18]. For high incident heat fluxes (i.e. $t_{ig} \to 0$), the time to ignition is obtained by performing a Maclaurin series expansion of the solution and making the surface temperature reach a pyrolysis or ignition temperature. Common solutions are of the form [12,18]:

$$\frac{1}{t_p^{1/2}} = \frac{2}{\sqrt{\pi}}\frac{1}{(k\rho c_p)^{1/2}}\frac{\dot{q}''_{ext}}{\theta(0,t_p)}, \tag{3}$$

where t_p, the pyrolysis time, is usually considered as being equal to the ignition time, t_{ig} [1,18]. Note that this problem does include convective and radiative losses at the surface of the solid through an effective heat transfer coefficient, but its solution is independent of h [18].

3.2. Solution for a ramped heat flux with no surface losses

Given the nature of the WUI ignition problem, solutions for constant incident heat fluxes are not desirable. To obtain more realistic boundary conditions, a ramping incident heat flux is considered. The solution for the particular case of a ramped incident heat flux with negligible heat losses at the surface and no initial constant heat flux is obtained from Carslaw and Jaeger [19, pp. 75–76], defining the incident heat flux as $\dot{q}''_{net}(t) = mt$. The solution for the time to ignition for high heat fluxes expressed in a similar form as Eq. (3) becomes,

$$\frac{1}{t_{ig}^{1/2}} = \frac{2}{\sqrt{\pi}}\frac{2}{3(k\rho c_p)^{1/2}}\frac{\dot{q}''_{net}(t_{ig})}{\theta_{ig}}. \tag{4}$$

3.3. Solution for a ramped heat flux with surface losses

A solution for the problem stated in Eq. (1) with a time-varying incident heat flux and convective losses at the surface is not readily

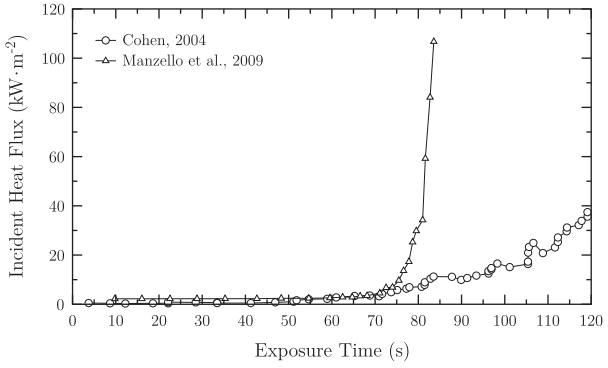

Fig. 1. Measured incident heat flux for wildfire tests, as reported by Cohen [9] and Manzello et al. [7].

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