Fire Safety Journal 82 (2016) 131–144

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Ignition of wood under time-varying radiant exposures

Matthew J. DiDomizio [a,*], Patrick Mulherin [b], Elizabeth J. Weckman [a]

[a] Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, ON, Canada N2L 3G1
[b] Sereca JENSEN HUGHES, Richmond, BC, Canada V6V 3E2

ARTICLE INFO

Article history:
Received 27 August 2015
Received in revised form
28 January 2016
Accepted 10 February 2016
Available online 22 February 2016

Keywords:
Ignition
Transient
Heat transfer
Model
Cone calorimeter
Wood

ABSTRACT

Many studies have utilized a small-scale experimental apparatus such as the cone calorimeter to investigate the piloted ignition of wood exposed to constant levels of incident heat flux; however, there is a deficiency of similar studies related to the non-piloted ignition of wood exposed to time-varying heat fluxes which might represent more realistic fire exposures. In this study, a method was established for producing well-controlled, time-varying exposures using the conical radiant heater of a cone calorimeter. Experiments were conducted in which the incident flux, time to non-piloted ignition, and back-surface temperature of spruce wood were measured. Measured data were used in combination with a numerical heat transfer model to compute the time-dependent temperature distribution through each specimen, and thereby deduce the surface temperature at ignition. From the 30 specimens tested, the average surface temperature for non-piloted ignition of wood was determined to be 521 ± 10 °C. From this surface temperature range, the heat transfer model was used to predict the range of time over which non-piloted ignition was likely to occur for a given time-varying exposure. This procedure was found to produce excellent predictions of ignition time for the time-varying exposures considered in this study. In addition, several existing ignition models were considered, and their suitability for predicting the non-piloted ignition of wood was assessed.

1. Introduction

There is an ongoing need to develop methods for predicting the thermal response and ignition of building materials exposed to fires. Of particular importance in this regard is prediction of the thermal response and ignition of solid materials under time-varying heat exposures. While there presently exists an abundance of literature on the piloted ignition of materials exposed to constant radiation-dominated incident flux, comparatively little research has been conducted on the response and non-piloted ignition of materials exposed to time-varying heating, a condition much more likely to be encountered in a real fire scenario. The purpose of this research, therefore, was to investigate and model the key physical processes driving the thermal response and flaming ignition of spruce wood when exposed to transient, radiation-dominated heating. Spruce dimensional lumber was selected for the study due to its widespread use as a framing material in North American construction.

2. Background

Various numerical and analytic methods have been developed to model the ignition of solid materials such as wood. Many of these methods use experimental data, often from a cone calorimeter or other small-scale fire test, to derive parameters such as a thermal inertia and convective heat transfer coefficient [1–4]. Many ignition models require some knowledge of the thermophysical properties of the material; the thermophysical properties of wood have been thoroughly investigated with respect to their variation with moisture content, temperature, and density [5–8]. Generic relations for temperature dependent material properties of softwood, such as those in Eurocode 5 [9], are available for general purpose fire safety calculations. Other research focused on the detailed pyrolysis of wood under exposure to radiant heat flux in a cone calorimeter apparatus [10–13]. Despite evidence to the contrary [14], surface properties for radiation heat transfer (absorptivity and emissivity) were often considered to be constant, with little account taken for changes that occur as a material heats, degrades, and chars on the surface. In consideration of this, Boulet et al. [15] modeled the radiative flux distribution with time across the surface of a plywood specimen under a cone heater and estimated values of average absorptivity for virgin and charred wood. In related work Bilbao et al. [16] modeled the transient degradation and ignition of wood, while Babrauskas [17] provided insight

* Corresponding author.
E-mail address: matt.didomizio@uwaterloo.ca (M.J. DiDomizio).

http://dx.doi.org/10.1016/j.firesaf.2016.02.002
0379-7112/

Nomenclature

α	thermal diffusivity ($m^2\ s^{-1}$)
Bi	Biot number (–)
c_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
ϵ_s	total surface emissivity (–)
Fo	Fourier number (–)
h_c	convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_e	effective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
L	thickness of a specimen (m)
q_c''	convective heat flux from the exposed surface ($W\ m^{-2}$)
q_{cr}''	critical heat flux for ignition ($W\ m^{-2}$)
q_i''	incident heat flux to the exposed surface ($W\ m^{-2}$)
q_{ign}''	incident heat flux at time t_{ign} ($W\ m^{-2}$)
q_{min}''	minimum heat flux for ignition ($W\ m^{-2}$)
q_{net}''	net heat flux to a surface ($W\ m^{-2}$)
q_o''	radiosity at the exposed surface ($W\ m^{-2}$)
ρ	density ($kg\ m^{-3}$)
σ	Stefan–Boltzmann constant ($W\ m^{-2}\ K^{-4}$)
t	time (s)
t_{ign}	time to ignition (s)
T	temperature at depth x and time t (K)
T_{ign}	temperature of the exposed surface at time t_{ign} (K)
T_s	temperature of the exposed surface at time t (K)
T_∞	temperature of ambient air (K)
x	position into the depth of a specimen (m)

on the history of wood ignition theory and data, and Shen et al. [18] reviewed several integral models for the prediction of wood ignition times.

From classical ignition theory for a thermally thick solid inert material under constant radiant exposure, the evolution of temperature within the material is determined from the one-dimensional heat equation with a uniform heat flux boundary condition on the exposed side:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)=\rho c_p\frac{\partial T}{\partial t}, \tag{1}$$

and

$$\left.\frac{\partial T}{\partial x}\right|_{x=0}=\frac{\epsilon_s}{k}q_i''-\frac{h_e}{k}(T_s-T_\infty), \tag{2}$$

where

$$h_e=\epsilon_s\sigma\left(T_s^2+T_\infty^2\right)\left(T_s+T_\infty\right)+h_c. \tag{3}$$

A one-dimensional thermal model is assumed in this problem formulation; the suitability of this simplification depends on the size and configuration of the specimen relative to the heat source. The exposed surface of the specimen is assumed to be opaque and gray with directionally and spectrally averaged radiative properties, and heat losses by convection and re-radiation. It is further assumed that the unexposed side of the specimen behaves as an adiabatic boundary (valid for thermally thick specimens), and that initially the specimen is at a uniform temperature equal to the temperature of the surrounding air. Since the mechanism for ignition is presumed to be the surface of a specimen reaching a critical temperature, the time to ignition may be determined by a solution to this heat transfer problem. It has been shown that a numerical approach may be used to solve this problem, thereby computing the time for the surface temperature of a material to reach a previously determined ignition temperature, and consequently predicting the time to ignition [19]. Additionally, a number of analytical and empirical approaches were developed over the years to solve or approximate a solution to this problem, and ultimately to predict the time to ignition of a material; several of these ignition models are discussed below in more detail.

2.1. Ignition under constant exposures

First, the case of constant incident heat flux exposure is considered. The Lawson and Simms [20] model is a classical analytical solution to the simplified heat transfer problem described above:

$$T_s(t)=\frac{q_i''}{h_e}\left[1-\exp(\tau)\mathrm{erfc}\left(\sqrt{\tau}\right)\right], \tag{4}$$

where

$$\tau=\frac{h_e^2}{k\rho c_p}t.$$

In this model, the surface of the specimen is assumed to be black ($\epsilon_s=1$) and radiative and convective losses are lumped into a single h_e term. Time to ignition is computed to be the time at which $T_s(t)=T_{ign}$. The surface temperature, $T_s(t)$, must be evaluated at each non-dimensional time, τ, which in turn depends on, h_e, which in turn must be re-evaluated at each time instance as $T_s(t)$ rises (see Eq. (3)). While this solution is mathematically complete, the methodology required does not readily allow for direct prediction of ignition time from experimental ignition data [21]. Additionally, it is cautioned that the product of an exponential function and a complementary error function may lead to numerical inconsistencies in calculations, depending on the solution method.

If it is assumed that there are no heat losses at the surface, an analytical solution to the heat transfer problem (i.e. see Mikkola and Wickman [22]) leads to an ignition model of the form:

$$t_{ign}=\frac{\pi}{4}k\rho c_p\left(\frac{T_{ign}-T_\infty}{q_i''}\right)^2. \tag{5}$$

Based on the observation of a linear relationship between q_i'' and $t_{ign}^{-0.5}$ in Eq. (5), Atreya [23] developed an integral solution that incorporates both convective and radiative losses at the surface of the specimen:

$$t_{ign}=M\left[\frac{\theta^2}{2F^2}-\frac{\theta(r+2S\theta)}{\beta F}+\frac{r}{\beta^{3/2}}\ln\left(\frac{\left(2S\theta+r-\sqrt{\beta}\right)\left(r+\sqrt{\beta}\right)}{\left(2S\theta+r+\sqrt{\beta}\right)\left(r-\sqrt{\beta}\right)}\right)\right], \tag{6}$$

where

$$\theta=T_{ign}-T_\infty;\quad M=\frac{2k\rho c_p}{3\epsilon_s^2};\quad S=-\frac{25}{3}\sigma T_\infty^2;$$

$$r=-\left(h_c+4\sigma T_\infty^3\right);\quad \beta=\left(r^2-4Sq_i''\right);$$

$$F=q_i''-h_c\theta-\sigma\left[\left(\theta+T_\infty\right)^4-T_\infty^4\right].$$

While Atreya's model is complex in the number of terms involved, it does provide a relatively straightforward means for computing the ignition time of a thermally thick material exposed to a constant incident heat flux.

The model of Tewarson [24] built upon Eq. (5) by accounting for heat losses via a critical heat flux term, which is subtracted from