IGNITION CONDITIONS FOR HOUSES EXPOSED TO EXTERNAL RADIATION SOURCED FROM ADJACENT BUSHFIRES

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ABSTRACT

The present work is dedicated to building up an ignition model for evaluating the fire risk of a structural component exposed to the external radiant heat flux sourced from bushfires. Based on the theory of one-dimensional heat transfer, analytical correlations for determining the ignition delay time and the energy absorbed by the targeted solid are worked out, which are a function of external radiation heat flux, wind speed and the solid thermal properties. Ignition delay times for various types of materials are then computed and compared with the available experimental data. Energy absorbed by the solids during their ignition process is also quantified, which decreases with increasing incident heat flux and is also a function of wind speed in general. Based upon the energy balance between energy uptake by a solid and the energy required for the thermal boundary layer on the solid surface to reach ignition status, a simplified ignition criterion is derived for an undried solid with fixed apparent thermal properties. Testing of the model with two independent experimental data sets shows that it may provide convenient and reliable predictions on the ignition delay times for moist materials located in the flowing environment. This model has application in engineering practice for predicting the ignition potential of a solid intercepting radiant heat sourced from a developing bushfire.

KEYWORDS: Ignition of solids, Ignition delay time, Radiant heat flux, Fire risk at urban interface

INTRODUCTION

A bushfire usually makes its impact on the built environment in adjacent areas, involving one or a combination of the following three heat transfer modes: flame radiation; flame impingement; and firebrands (embers lofted from a fire front). Post-fire surveys of houses destructed at urban interface indicate that the combined attack of flame radiation and firebrands is the most harmful mechanism leading to the ignition of houses adjacent to a bushfire [1,2]. This phenomenon can often be classified as 'piloted ignition'; once radiation intercepted by a house component (e.g. a wooden wall) results in a substantial temperature rise on its surface, firebrands then play a role in igniting the combustible volatiles released from the solid.

Assessment of the survival ability of houses at the wildland and urban interface is an important practice in protecting properties in bushfire-prone areas, which can be done by developing a mathematical model for evaluating the ignition potential of a house due to its exposure to the radiative heat sourced from an adjacent bushfire. This work was pioneered by the scientists working in the Rocky Mountain Fire Sciences Laboratory in Missoula, Montana, USA [2]. In 1996, Cohen and Butler [2] proposed a model for determining the time required for igniting a structural component, with the ignition criterion established by integrating the incident heat flux over the entire duration prior to ignition and setting the minimum energy for igniting a type of wood material. This model was then used to determine the safe separation distance between houses and wildland fuels at the urban interface.

In fact, the core in evaluating the survival potential of a structural component in bushfire-prone areas is just an ignition problem, i.e. ignition of a solid combustible exposed to an external radiant heat flux in the presence of a pilot. Although the ignition of organic materials has been extensively studied using cone calorimetric techniques or with numerical simulations and many correlations have been generated [3-8], unfortunately the established understanding and associated correlations have not met all the requirements for this sort of assessment. This is partially due to the fact that existing ignition studies based upon bench-scale measurements have not taken into account the situation where a moist solid receives transient radiant heat flux in a flowing environment, which is the reality for a structural component located at the urban interface. The flux-time-product (FTP) model adopted by Cohen and Butler [2] is applicable to the scenario where the incident heat flux is a variable. However, due to its empirical nature this model is limited when applied to an undried solid intercepting radiative heat and undergoing convective heat loss. It is intuitive that once a house at the wildland and urban interface is under attack from a bushfire, the ignition process should be significantly affected by the local weather conditions including wind speed [6,9].

The present work aims at establishing an ignition model for a house component exposed to a radiant heat flux taking into account its drying status and cooling effect of the local wind. By resolving the one-dimensional heat transfer problem, analytical solutions are found for determining the ignition delay time and the energy absorbed by the solid during the ignition process. Characteristics of the energy uptake are then explored for various types of materials and local wind speeds. Based upon the energy balance between energy uptake and the energy required for the thermal boundary layer at solid surface to reach ignition status, a correlation is eventually developed to determine the ignition delay time for an undried solid exposed to a variable incident heat flux.

MATHEMATICAL MODEL

A flat side wall of a house, made of a combustible material (e.g. a type of wood), is exposed to radiation from a fire front in a bushfire. The radiant heat flux is maintained at a level of $\dot{q}''_{rad}$, and is normally incident onto the surface of the wall with a uniform distribution across the wall surface (Fig. 1). The wall has a uniform absorptivity of β on its surface, and is thick enough to be considered as thermally thick. The continuous heat flow into the solid leads to a temperature rise on the solid surface and within the solid. A local wind blows in a direction parallel to the solid surface, and forms a laminar/turbulent boundary layer on the wall surface. As a result, a fraction of the energy absorbed by the solid is removed by the forced convection. Ignition occurs when the surface temperature reaches a critical value T_{ig}.

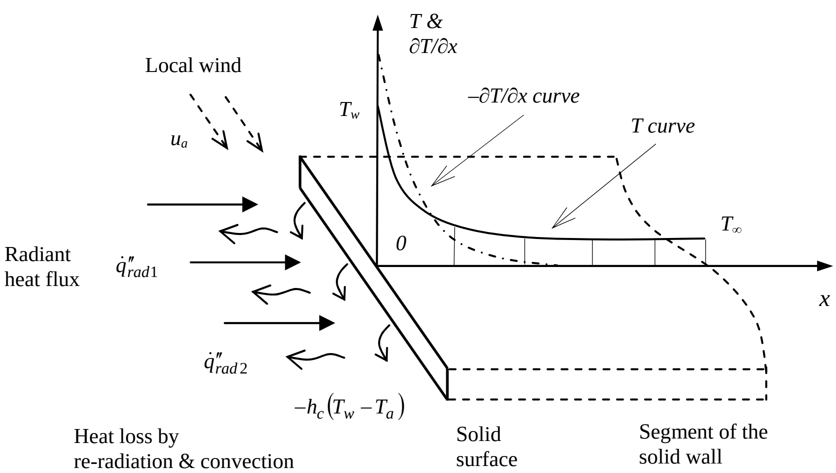

FIGURE 1. Schematic diagram of a wall exposed to the external radiation heat flux

The governing equation for determining the temperature rise on the solid surface and within the solid is given by:

$$\rho_s C_{ps} \frac{\partial T}{\partial t} = k_s \frac{\partial^2 T}{\partial x^2} \qquad [1]$$

This equation is subject to the following boundary condition on the solid surface:

$$-k_s \frac{\partial T_w}{\partial x} + h_{eq}\left(T_w - T_a\right) = \beta \dot{q}''_{rad} \qquad [2]$$

and the initial condition:

$$T_0 = T_a \qquad [3]$$

where h_{eq} stands for the equivalent coefficient of heat transfer due to forced convection and re-radiation between the heated solid surface and the cold environment, which is defined as:

$$h_{eq} = h_c + \varepsilon\sigma\left(T_w + T_a\right)\left(T_w^2 + T_a^2\right) \qquad [4]$$

This parameter is often treated as a constant for simplicity by evaluating the wall surface temperature at a typical value throughout the ignition process [3-5,10]. The convective heat transfer coefficient h_c can be determined by the following empirical correlations [11,12]:

$$\frac{h_c L}{k_g} = 0.664\left(\frac{\rho_g u_a L}{\mu_g}\right)^{1/2}\left(\frac{\mu_g C_{pg}}{k_g}\right)^{1/3} \qquad \left(\frac{\rho_g u_a L}{\mu_g} < 5\times10^5\right) \qquad [5a]$$

$$\frac{h_c L}{k_g} = 0.037\left[\left(\frac{\rho_g u_a L}{\mu_g}\right)^{4/5} - 871\right]\left(\frac{\mu_g C_{pg}}{k_g}\right)^{1/3} \qquad \left(\frac{\rho_g u_a L}{\mu_g} \geq 5\times10^5\right) \qquad [5b]$$

By defining $\theta = T - T_a$, Eqs. [1] to [3] can be re-written as:

$$\frac{\partial \theta}{\partial t} = \alpha_s \frac{\partial^2 \theta}{\partial x^2} \qquad [6]$$

$$-\frac{\partial \theta_w}{\partial x} + h\theta_w = \frac{\beta \dot{q}''_{rad}}{k_s} \qquad [7]$$

$$\theta_0 = 0 \qquad [8]$$

where α_s represents $k_s/(\rho_s C_{ps})$ and h denotes h_{eq}/k_s.

The exact solution of Eq. [6] in conjunction with the boundary and initial conditions (Eqs. [7] and [8]) has been given by Carslaw and Jaeger [13], i.e.

$$\theta = \frac{\beta \dot{q}''_{rad}}{h k_s}\left[erfc\left(\frac{x}{2\sqrt{\alpha_s t}}\right) - e^{hx + h^2 \alpha_s t} erfc\left(\frac{x}{2\sqrt{\alpha_s t}} + h\sqrt{\alpha_s t}\right)\right] \qquad [9]$$

By utilising the concept of ignition temperature, a criterion for igniting a combustible on its surface can be written by:

$$T_{ig} - T_a = \frac{\beta \dot{q}''_{rad}}{hk_s}\left[1 - e^{h^2\alpha_s t_{ig}} erfc\left(h\sqrt{\alpha_s t_{ig}}\right)\right] \qquad [10]$$

Equation [10] is not suitable for determining the ignition delay time due to the presence of an infinite series of complicated functions, which is a classic issue in ignition studies. Thus, an accurate approximation for the complementary error function (relative error < 0.1%) is invoked [14], that is

$$erfc\left(h\sqrt{\alpha_s t}\right) = \left[\frac{0.348}{1 + 0.471h\sqrt{\alpha_s t}} - \frac{0.096}{\left(1 + 0.471h\sqrt{\alpha_s t}\right)^2} + \frac{0.748}{\left(1 + 0.471h\sqrt{\alpha_s t}\right)^3}\right] e^{-h^2\alpha_s t} \qquad [11]$$

Substitution of Eq. [11] into Eq. [10] with slight re-arrangement leads to:

$$\begin{aligned}\frac{\left[hk_s\left(T_{ig} - T_a\right) - \beta\dot{q}''_{rad}\right]}{\beta\dot{q}''_{rad}}\left(1 + 0.471h\sqrt{\alpha_s t_{ig}}\right)^3 + 0.348\left(1 + 0.471h\sqrt{\alpha_s t_{ig}}\right)^2 \\ - 0.096\left(1 + 0.471h\sqrt{\alpha_s t_{ig}}\right) + 0.748 = 0\end{aligned} \qquad [12]$$

which makes it possible to determine the ignition delay times analytically.

The temperature gradient on the solid surface and within the solid is determined by differentiating θ over x, that is

$$-\frac{\partial T}{\partial x} = \frac{\beta\dot{q}''_{rad}}{hk_s}\left\{\begin{aligned}&\frac{1}{\sqrt{\pi\alpha_s t}}\exp\left(-\frac{x^2}{4\alpha_s t}\right) + h\exp\left(hx + h^2\alpha_s t\right) erfc\left(\frac{x}{2\sqrt{\alpha_s t}} + h\sqrt{\alpha_s t}\right) \\ &-\frac{1}{\sqrt{\pi\alpha_s t}}\exp\left(hx + h^2\alpha_s t\right)\exp\left[-\left(\frac{x}{2\sqrt{\alpha_s t}} + h\sqrt{\alpha_s t}\right)^2\right]\end{aligned}\right\} \qquad [13]$$

Thus, the rate of heat flow into the surface of the wall is determined by:

$$-k_s\frac{\partial T_w}{\partial x} = \beta\dot{q}''_{rad} e^{h^2\alpha_s t} erfc\left(h\sqrt{\alpha_s t}\right) \qquad [14]$$

The energy absorbed by the solid during the ignition process is then given by:

$$E_{ig} = \int_0^{t_{ig}} \beta\dot{q}''_{rad} e^{h^2\alpha_s t} erfc\left(h\sqrt{\alpha_s t}\right) dt \qquad [15]$$

A further utilisation of Eq. [11] gives rise to:

$$E_{ig} = \frac{2\beta\dot{q}''_{rad}}{(0.471h)^2\alpha_s}\left[\begin{aligned}&0.164h\sqrt{\alpha_s t_{ig}} - 0.444\ln\left(1 + 0.471h\sqrt{\alpha_s t_{ig}}\right) \\ &-\frac{0.844}{1 + 0.471h\sqrt{\alpha_s t_{ig}}} + \frac{0.374}{\left(1 + 0.471h\sqrt{\alpha_s t_{ig}}\right)^2} + 0.470\end{aligned}\right] \qquad [16]$$

Equation [16] clearly reveals a dependence of the energy uptake on several parameters, including incident heat flux, wind speed and the thermal properties of the solid, as well as the ignition delay time.

RESULTS AND DISCUSSION

Equation [12] was utilised to evaluate the thermal response of dried solids located in a still or flowing environment and exposed to an external heat flux varying between 15 and 100 kW/m^2. Four types of materials were considered, with their property data given in Table 1. In the determination of h_{eq}, the mean wall surface temperature was set at $\left(5T_{ig} + T_a\right)/6$, an estimation based upon the surface temperature histories recorded during the ignition measurements using cone calorimeters [5,9]. The setting of the minimum external radiant heat flux at 15 kW/m^2 allows an effective radiation heat flux intercepted by a solid to be higher than 10 kW/m^2, which is actually a threshold for igniting a usual solid [6-8,15].

TABLE 1. Evaluation of parameters utilised in the calculations [3,5,6,16,17]

Material	Density (kg/m^3)	Apparent $\rho_s C_{ps} k_s$ (kJ^2/(m^4 K^2 s)	Ignition temperature (K)	Surface absorptivity
Radiata pine [3,5]	460	0.123	622	0.85
Pinus Pinaster [6]	460	0.210	652	0.78
Red oak [17]	660	0.397	633	0.85
PMMA [16]	1200	0.857	636	0.90

Dependence of the ignition delay time on the incident radiation level has been examined using Eq. 12, with the results shown in Fig. 2. The ignition delay time illustrates a monotonic decrease with increasing the radiation heat flux. At an incident heat flux of 15 kW/m^2, the ignition delay time is in a vast range of between ~200 and ~1200 s for the materials having different thermal inertia values; when the radiation level reaches 100 kW/m^2, the ignition delay time essentially drops to <10 s. As shown in Fig. 2, the predicted results are in good agreement with the experimental data collected during the measurements for these four types of materials using cone calorimeters [5,6,16,17].

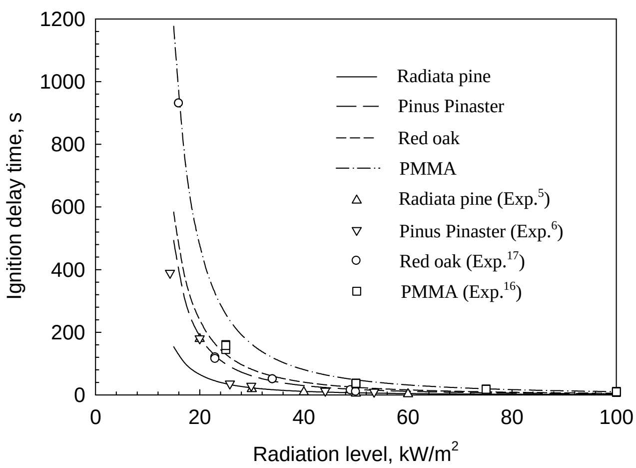

FIGURE 2. Effect of external heat flux on the ignition delay times for materials with distinct apparent thermal inertia values.

The ignition delay time as a function of wind speed for different levels of incident heat flux is shown in Fig. 3. For a side wall made of Radiata Pine wood with a characteristic scale of 5 m and subjected to an incident heat flux of 25 kW/m^2, the ignition delay time increases from ~40 to ~110 s as the wind speed increases from 0 to 10 m/s. The continuously-increasing trend becomes insignificant once the solid is exposed to an external radiant heat flux higher than 35 kW/m^2. For an incident heat flux of 55 kW/m^2, the ignition delay time is almost independent of wind speed. The same pattern is exhibited in the plot for the PMMA material. These observations are consistent with the experimental findings reported by Bilbao *et al.* [6] for *Pinus Pinaster* wood samples.

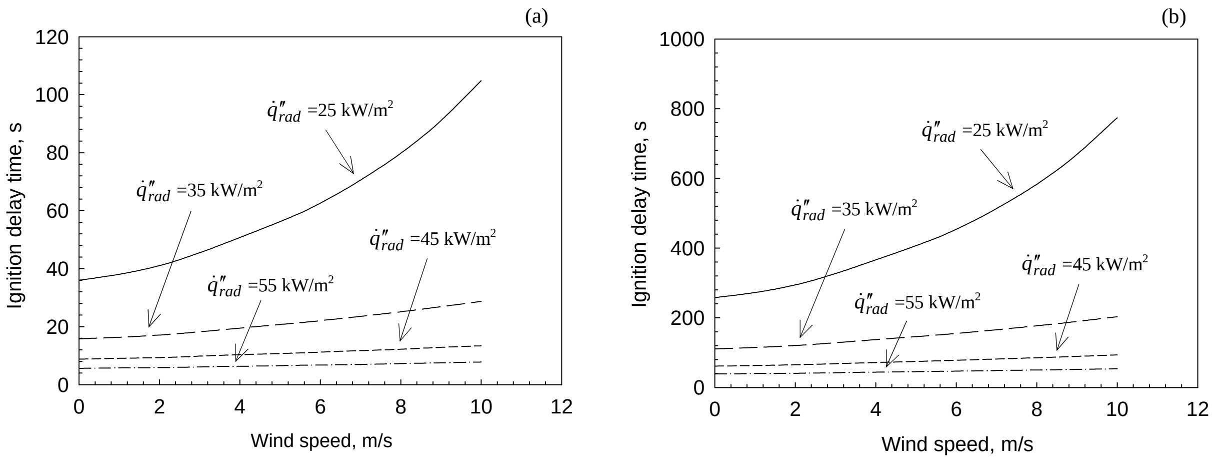

FIGURE 3. Ignition delay time as a function of wind speed for a solid composed of Radiata pine wood (a) and PMMA material (b) with surface absorptivities of 0.85 and 0.90, respectively

Energy uptake by a solid wall during the ignition process has been predicted using Eq. 16 for different types of materials, with the results displayed in Fig. 4. It is observed that the amount of heat flow into a solid prior to ignition decreases consistently with increasing radiation heat flux, with the level of variation closely related to the solid's thermal inertia value. For the Radiata pine wood with a thermal inertia value of 0.123 kJ^2/(m^4 K^2 s), the magnitude of E_{ig} varies between ~10^2 and ~10^3 kJ/m^2 for an incident heat flux of between 15 and 100 kW/m^2; while for the PMMA material with a thermal inertia value of 0.857 kJ^2/(m^4 K^2 s), the range of E_{ig} is between ~10^3 and ~10^4 kJ/m^2. The results computed for the PMMA material have also demonstrated good agreement with a set of experimental data reported by Babrauskas [8].

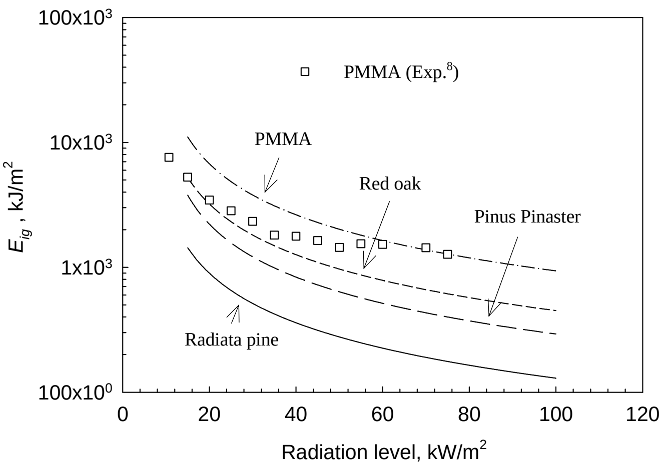

FIGURE 4. Energy absorbed by the solid during the ignition process for four types of materials

The effect of wind speed on the energy absorbed by two different types of materials is shown in Fig. 5. For the Radiata pine wood and PMMA material, once they are exposed to an incident heat flux of 25 kW/m^2, the amount of energy absorbed increases significantly with increasing wind speed. However, this trend becomes insignificant at an elevated incident heat flux, and once the incident heat flux reaches 55 kW/m^2, the amount of energy absorbed by the solid tends to be independent of the wind speed. The pattern observed in the plots of the energy absorbed versus the wind speed is actually a reflection of the impact of wind speed on the ignition delay time.

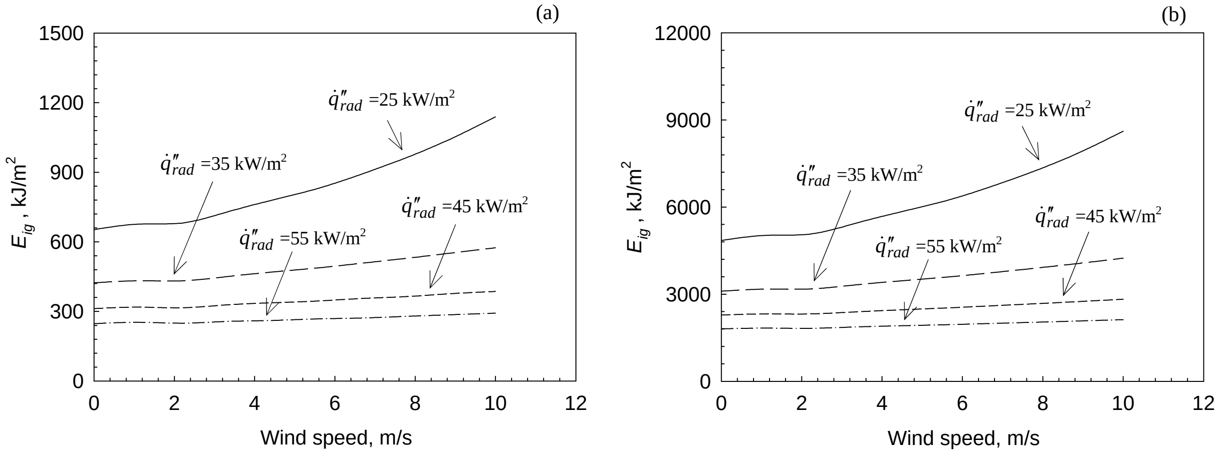

FIGURE 5. Amount of heat flown into the solid as a function of local wind speed, evaluated for a solid having a thermal inertia value of 0.123 (a) or 0.857 kJ^2/(m^4 K^2 s) (b)

Behaviour of the energy absorbed by a solid during the ignition process can be further analysed using Eq. [15]. For a large value of the term $h\sqrt{\alpha_s t}$, we have [13,14]:

$$erfc\left(h\sqrt{\alpha_s t}\right) = erfc\left(h_{eq}\sqrt{\frac{t}{\rho_s C_{ps} k_s}}\right) \approx \frac{1}{h_{eq}}\sqrt{\frac{\rho_s C_{ps} k_s}{\pi t}}\exp\left(-\frac{h_{eq}^2 t}{\rho_s C_{ps} k_s}\right) \qquad [17]$$

Substitution of Eq. [17] into Eq. [15] yields:

$$E_{ig} \approx \frac{\beta \dot{q}''_{rad}}{h_{eq}}\int_0^{t_{ig}}\sqrt{\frac{\rho_s C_{ps} k_s}{\pi t}}dt = \frac{2\beta \dot{q}''_{rad}}{h_{eq}}\sqrt{\frac{\rho_s C_{ps} k_s t_{ig}}{\pi}} \qquad [18]$$

This equation confirms the trend in the dependence of E_{ig} on t_{ig}, although it is not accurate for the determination of E_{ig} when $h\sqrt{\alpha_s t}$ is moderately large. The apparent proportionality of E_{ig} to $\beta \dot{q}''_{rad}$ or h_{eq}^{-1} is not real, since t_{ig} varies inversely with increasing $\beta \dot{q}''_{rad}$ or h_{eq}^{-1}, as shown in Figs. 2&3. The proportionality of E_{ig} to $\sqrt{\alpha_s t_{ig}}$ at constant $\beta \dot{q}''_{rad}$ and h_{eq} directly points to the relationship between the energy uptake by the solid prior to ignition and the scale of the thermal boundary layer formed on the solid surface.

On the other hand, when the term $h\sqrt{\alpha_s t}$ is always very small during the ignition process, we have [13]:

$$erfc\left(h\sqrt{\alpha_s t}\right) = erfc\left(h_{eq}\sqrt{\frac{t}{\rho_s C_{ps} k_s}}\right) \approx 1 - \frac{2}{\sqrt{\pi}} h_{eq}\sqrt{\frac{t}{\rho_s C_{ps} k_s}} \qquad [19]$$

From Eq. [15] and Eq. [19], we obtain:

$$E_{ig} \approx \beta \dot{q}''_{rad} \int_0^{t_{ig}} \left(1 + h_{eq}^2 \frac{t}{\rho_s C_{ps} k_s}\right)\left(1 - \frac{2}{\sqrt{\pi}} h_{eq} \sqrt{\frac{t}{\rho_s C_{ps} k_s}}\right) dt \qquad [20]$$

where the exponential term in Eq. [15] has been replaced by the first-order term in Taylor's series. By omitting the higher-order powers of $h_{eq}\sqrt{\frac{t}{\rho_s C_{ps} k_s}}$, the ignition delay time is then approximately given by:

$$E_{ig} \approx \beta \dot{q}''_{rad} \left(1 - \frac{4}{3\sqrt{\pi}} h_{eq} \sqrt{\frac{t_{ig}}{\rho_s C_{ps} k_s}}\right) t_{ig} \qquad [21]$$

At condition of $\frac{4}{3\sqrt{\pi}} h_{eq} \sqrt{\frac{t_{ig}}{\rho_s C_{ps} k_s}} \to 0$, $E_{ig} \to \beta \dot{q}''_{rad} t_{ig}$. This implies that in the case of a solid exposed to a very high level of external radiation, the energy absorbed by the solid through the ignition process is essentially the product of the effective radiation heat flux and the ignition delay time, independent of the equivalent heat transfer coefficient. Equation [21] highlights the fact that, once ignition is achieved within about a few seconds, the heat loss by forced convection and re-radiation becomes negligible compared to the energy absorbed by the solid during the ignition process.

A well-established understanding [4,8,18] for a thermally thick material is that ignition may occur once the solid absorbs sufficient energy within the thermal boundary layer at a scale of $\sqrt{\alpha_s t_{ig}}$. Thus, an energy balance can be written in the form:

$$E_{ig} = c_s Q_{ig} \sqrt{\alpha_s t_{ig}} \qquad [22]$$

where Q_{ig} is defined as the heat required for a solid to reach ignition status, that is $\rho_s C_{ps}(T_{ig} - T_a)$ for a dried material. The coefficient c_s is found to be unity by a least-square regression fit with the results of E_{ig} determined for different types of materials and at various wind speeds. A further confirmation of the energy balance is shown in the plots of $Q_{ig}\sqrt{\alpha_s t_{ig}}$ versus E_{ig} (Fig. 6).

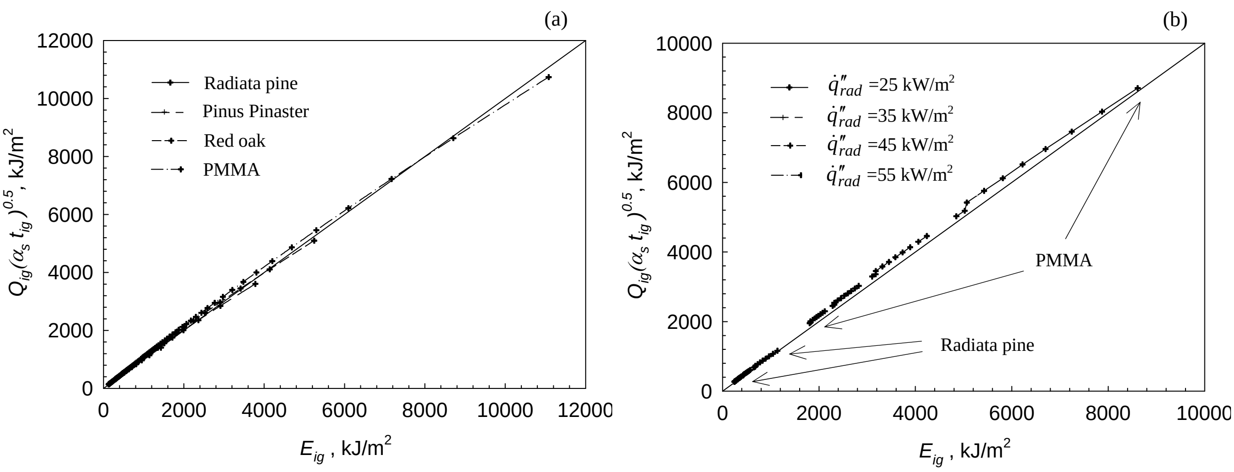

FIGURE 6. Relationship between $Q_{ig}\sqrt{\alpha_s t_{ig}}$ and E_{ig} for solids exposed to external radiation heat flux at different levels in still air (a) and for Radiata pine wood as well as PMMA material intercepting radiant heat in a flowing environment (b)

Noting that $E_{ig} = \int_0^{t_{ig}} \left(\beta\dot{q}''_{rad} - \dot{q}''_{los}\right)dt$, we have:

$$\beta\dot{q}''_{rad}t_{ig} - 0.67\dot{q}''_{cr}t_{ig} = Q_{ig}\sqrt{\frac{k_s t_{ig}}{\rho_s C_{ps}}} \qquad [23]$$

where $\dot{q}''_{cr}$ denotes the total heat loss at ignition, i.e. $h_c\left(T_{ig} - T_a\right) + \varepsilon\sigma\left(T_{ig}^4 - T_a^4\right)$. Equation [23] is actually a simplified criterion for ignition. By replacing Q_{ig} with $\rho_s C_{ps}\left(T_{ig} - T_a\right)$, Eq. [23] can be derived in a form very close to those developed either by using the integral method [18] or empirical fitting of the experimental data [8].

A general form of the ignition criterion for an undried solid exposed to a non-constant radiation heat flux can be expanded to:

$$\int_0^{t_{ig}} \beta\dot{q}''_{rad}(t)dt = \left[\left(1 - m_f\right)\left(T_{ig} - T_a\right) + m_f\left(373 - T_a\right)\frac{C_{pw}}{C_{ps}} + m_f\frac{L_v}{C_{ps}}\right]\sqrt{\rho_s C_{ps} k_s t_{ig}} + 0.67\dot{q}''_{cr}t_{ig} \qquad [24]$$

which is still an energy balance between energy flowing into the solid and the energy required for the thermal boundary layer of the solid to reach ignition status.

The reliability of Eq. [24] has been tested with two sets of experimental data available in the literature with the results reported in Figs. 7 and 8. As shown in Fig. 7, the predicted results fit for the experimental data very well, even better than those determined by Eq. [12]. This may be due to the fact that the experimental data were collected for the samples containing ~8% water and the heat withdrawn by the solid drying was not considered in the one-dimensional heat conduction equation.

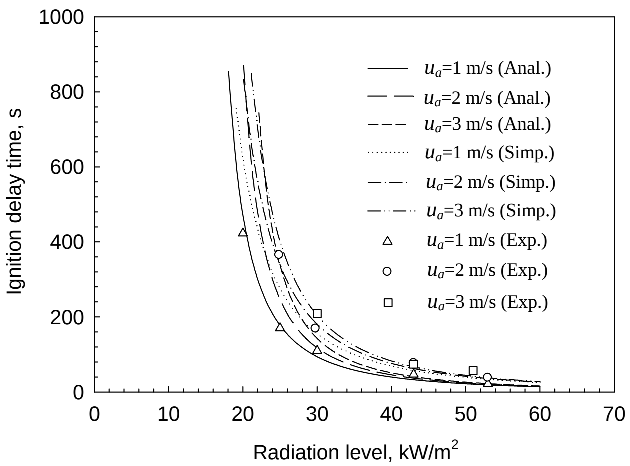

FIGURE 7. Comparison of the predicted ignition delay times with the results collected during piloted ignition measurements in a flowing environment [6]. Experiments were carried out with *Pinus Pinaster* wood specimens of 110×110×19 mm and containing 9% moisture.

As shown in Fig. 8, testing of the model is also very satisfactory with a set of experimental data exhibiting a dependence of the ignition delay time on the sample water content, although the effect of moisture content on the solid thermal properties and ignition temperature is not considered in the present calculations. Relationship between t_{ig} and Q_{ig} can be found from $t_{ig}^{-0.5} \propto Q_{ig}^{-1}\left(\dot{q}''_{rad} - 0.67\dot{q}''_{cr}\right)$

(refer to Eqs. [23] and [24]). With the increase in the moisture content, Q_{ig} increases significantly; for example, a doubled value of Q_{ig} for Radiata pine wood containing 21% moisture compared to that for a dried one. This means that an increase in the moisture content will result in significant decease in the slope of the plot of $t_{ig}^{-0.5}$ versus $\dot{q}''_{rad}$, which is in agreement with the experimental findings reported in the literature [5,9].

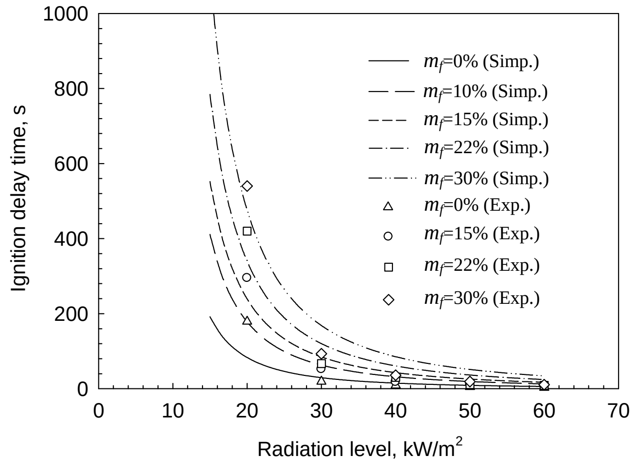

FIGURE 8. Ignition delay times calculated for Radiata pine wood at different levels of moisture content, in comparison with the experimental data collected using a cone calorimeter [5]

The ignition criterion described by Eq. [24] was developed for engineering purposes. As far as we know, this may be the only simple correlation so far for determining the ignition delay time taking into account the effect of moisture content. In the literature [5,9], the observed relationship between $t_{ig}^{-0.5}$ and $\dot{q}''_{rad}$ for undried samples is attributed to the altered thermal inertia value of the solid containing moisture, which prevents a prediction of the ignition delay times for undried samples due to their unknown *apparent* thermal inertia values. In addition, this implication may be depart from the physical nature occurred in the ignition process. Since the thermal properties of water are fairly close to the apparent thermal properties of wood in most cases, except for the latent heat of evaporation, the thermal properties of a solid should not be altered significantly by the addition of a small amount of moisture. Once an undried solid absorbs energy from external heat source, the temperature rise of water and its subsequent vaporisation are two essential steps occurring at an early stage of the ignition process, as exhibited in the temperature histories recorded during the ignition measurements [5,9]. For the majority of the time prior to ignition, the temperature on the solid surface varies at a level far above the boiling temperature of water, indicating that the impact of moisture content on the solid thermal properties is negligible at the later stage of the ignition process. It seems more plausible that the ignition process is affected by moisture through its adjustment in the heat required for the solid to reach the ignition status rather than its alteration in the solid *initial* thermal properties.

Using a numerical approach [6,8], ignition of a moisture-containing solid can be studied by tracing the temperature rise within the solid, water evaporation, solid pyrolysis and mass released from the solid. This is achievable by solving a group of partially differential equations governing the continuity, momentum, energy and mass balance for solid and water in conjunction with assumed ignition temperature and kinetic data for solid pyrolysis; the role of water in the ignition process can be analysed in detail at the same time. However, compared to the criterion introduced by Eq. [24], this approach is definitely too complicated to be applied in engineering practice.

Although the reliability of Eq. [24] should be further validated with more experimental data, there is no doubt that the application of this criterion will definitely simplify the procedure for evaluating the fire risk of houses raised by a potential bushfire occurring in adjacent areas, which allows the engineers to focus on the quantification of the transient radiation heat sourced from a fire front during its growth and extinction in their assessment practice.

CONCLUSIONS

Based upon the theory of one-dimensional heat transfer, an analytical model has been developed for determining the minimum time required for igniting a structural component exposed to an external radiation source in a flowing environment. The model also enables the quantification of the energy absorbed by the targeted solid during the ignition process. Examination of the amount of heat flowing into the solid for four types of combustibles shows that the energy absorbed during the ignition process decreases with the increase of the radiation heat flux, increases with the increase in the wind speed in general, and also is proportional to the depth of the thermal boundary layer within the solid. The balance between the energy uptake and the energy required for the thermal boundary layer on the solid surface to reach ignition status yields the following simplified ignition criterion

$$\int_0^{t_{ig}} \left(\beta \dot{q}''_{rad} - 0.67\dot{q}''_{cr}\right) dt = Q_{ig}\sqrt{\alpha_s t_{ig}}$$

which allows to determine the ignition delay time for a moisture-containing solid with known thermal properties and ignition temperatures. This engineering-oriented model offers a convincing interpretation on the effect of moisture content on the ignition delay time and demonstrates excellent agreement with two independent experimental data sets collected for undried solids located in a flowing environment. It has the potential to be applied in practice for evaluating fire risk at the urban interface.

NOMENCLATURE

C_p	specific heat (J/(kg K); C_{pg} = 1000 J/(kg K))
E_{ig}	energy absorbed by a solid throughout the ignition process (J/m^2)
h	h_{eq}/k_s
h_c	convective heat transfer coefficient (W/(m^2 K))
h_{eq}	equivalent coefficient of heat transfer induced by forced convection and radiation between a solid surface and the cold environment (W/(m^2 K))
k	thermal conductivity (W/(m K); k_g = 0.025 W/(m K))
L	characteristic length of a side wall (5 m)
m_f	moisture content of a solid
$\dot{q}''_{rad}$	rate of radiant heat flux impacting on the surface of a side wall of a house (W/m^2)
$\dot{q}''_{los}$	rate of heat loss by forced convection and re-radiation (W/m^2)
Q_{ig}	heat required for a solid to reach ignition status (J/m^3)
t	time (s)
T	temperature (K; T_a = 298 K)
u_a	wind speed (m/s)
x	distance starting from the wall surface (m)

Greek symbols

α_s	$k_s/\rho_s C_{ps}$
β	absorptivity of the solid surface
ε	emissivity of the solid surface ($\varepsilon = \beta$)
θ	temperature rise above the ambient (K)
μ_g	dynamic viscosity of air (1.81 × 10^{-5} kg/(m s))

ρ air density (kg/m^3; ρ_g = 1.2 kg/m^3)
σ Stefan-Boltzmann constant (5.67×10^{-8} W/(m^2 K^4))

Subscripts

0 initial
g gas phase
ig ignition
s solid phase
w surface of the side wall of a house
a ambient

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