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Author	Family Name	**Urban**
	Particle	
	Given Name	**James L.**
	Suffix	
	Division	Department of Mechanical Engineering
	Organization	University of California Berkeley
	Address	Berkeley, CA, USA
	Email	jlurban@berkeley.edu
Corresponding Author	Family Name	**Fernandez-Pello**
	Particle	
	Given Name	**A. Carlos**
	Suffix	
	Division	Department of Mechanical Engineering
	Organization	University of California Berkeley
	Address	Berkeley, CA, USA
	Email	ferpello@me.berkeley.edu

Ignition

James L. Urban and A. Carlos Fernandez-Pello
Department of Mechanical Engineering,
University of California Berkeley, Berkeley,
CA, USA

Definition

Ignition is defined here as the process leading to the onset of a sustained combustion reaction between a combustible material and an oxidizer, typically air, which results in the release of heat. The combustible material may be in the gaseous, liquid, or solid phase. Ignition can also refer to the original cause of the fire or the point when a specific fuel element is ignited such as a structure. The combustion reaction may be either a homogeneous gas phase reaction (flaming ignition) or a heterogeneous surface reaction (smolder ignition). For either combustion reaction to occur, the temperature of the fuel and air must first be elevated above a certain value, often termed the "ignition temperature," so that the heat released by the combustion reaction is larger than the heat losses from the reaction. However, this "ignition temperature" is not a property of the fuel material alone as it also depends on the circumstances in which the fuel is being ignited. Thus, the onset of ignition would occur by increasing the combustible material temperature with an external heat source (spark, pilot flame, hot surface, radiant source) and by ensuring that the temperature of the reactants remains high so that their combustion reaction overcomes the heat losses to the surrounding.

Introduction

The ignition of a solid fuel is obviously a critical process in the initial development of a fire. It must be recognized however that without the subsequent spread of the flames throughout the fuel, ignition may be inconsequential. Because of its importance in the onset of fire, ignition of solid combustibles has been studied intensively. There are excellent reviews published on solid fuel ignition. Particularly notable is the compendium of works on the subject of fuel ignition (Babrauskas 2003). There are also reviews that address specific subjects of the ignition process of continuous solid fuels (Cote 2003; Fernandez-Pello 1994, 2011; Atreya 1998; Quintiere 2006; Torero 2016; Kanury 1988; Drysdale 2011). However, despite the obvious importance of wildland fires, very few studies have been conducted specifically on the ignition of wildland fuels (Mcallister and Weise 2017; Fernandez-Pello 2011, 2017; Mindykowski et al. 2011; Consalvi et al. 2011). While ignition and flame spread are different, flame spread is essentially the ignition of successive fuel elements with a flame as the source of heating and ignition. Thus, ignition also has relevance in the propagation of a fire. One hallmark ignition source of the ~~WUI~~ fires

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replace with: "Wildland-Urban Interface (WUI)"

are firebrands (also known as embers): pieces of burning debris which can be lifted by the wind to a yet unreacted fuel. This is possible because the burning process reduces the weight of the firebrand enabling lofting. The topic of ignition by firebrands/embers is discussed some in this chapter. The initial threat of a ~~wildland-urban interface (~~WUI~~)~~ fire is firebrands, flame contact from burning vegetation in wildland areas or landscaping adjacent the structure, and radiation from the flame. After an initial structure ignition, the burning of the structure can produce more firebrands (Suzuki et al. 2012), allowing for the fire to spread further in the community through firebrand spotting.

Both WUI and wildland fuels include accumulations of finer natural fuels, but structure fuels are also relevant for WUI fire. Structures are primarily nonporous solid combustible materials, their ignition characteristics are well studied, and there are multiple sources of information about the problem in the literature (Cote 2003; Fernandez-Pello 1994, 2011; Atreya 1998; Quintiere 2006; Torero 2016; Kanury 1988; Drysdale 2011). There are of course commonalities between wildland and WUI fires in terms of how they are ignited. However, many structure fuels have different characteristics (i.e., chemical, thermal, and morphological) which are vastly different than wildland fuels which are also present due to their proximity to wildland areas.

In general, the vast majority of wildland fires are caused by humans – either deliberately or accidentally (Balch et al. 2017); this encompasses the US Forest Service-designated categories: equipment use, smoking, campfire, railroad, arson, debris burning, children, fireworks, power lines, structure, and miscellaneous fires (Balch et al. 2017). Alternatively, the only natural ignition causes are spontaneous ignition, lightning strikes, or heating from volcanic activity. While the idea of a solid fuel igniting may seem conceptually simple, characterizing ignition based on the controlling physical mechanisms can be quite difficult as there are numerous processes involved.

On the most basic level, the most stringent requirement is that heat must be added to the fuel so that a combustion reaction of the fuel and air, either heterogeneous surface reaction/smolder or a homogeneous gas phase reaction/flame, is initiated. Once initiated the combustion reaction must produce more heat than is lost to the surrounding environment, so that the reaction is sustained. However, describing the ignition of a solid fuel is particularly complicated because it also encompasses complexities of the condensed phase thermochemistry. Thus, there are the additional physiochemical processes describing how the solid fuel is thermally decomposed so that it can react with air in the fuel surface or turned into a gaseous fuel which in turn can burn with air (T'ien et al. 2001). This chapter presents an overview of the physical processes that play a role on the ignition of wildland fuels, what types of fuels are ignited, and the description of several fundamental ignition sources.

Common Fuels First Ignited

replace cause with : "first fuel ignited"

Wildland Fuels

In the ignition of natural wildland fuels, the easiest and most common type of fuel to be ignited is fine fuels such as grass, leaves, needles, chaff, mulch, and compost. This is because the large void fraction of these fuels allows the top layer burn with good availability of oxygen while thermally insulating the bottom of the burning layer. The NFPA reports that overall "light vegetation, including grass" is the ~~cause~~ of 66% of all outdoor fires and 83% of grass fires in the USA (Ahrens 2013). These finer fuels are often referred to as "1-h fuel" because the fuel reaches the moisture level of the surrounding environment in the timescale of an hour. Thus, on a hot day, these 1-h fuels could dry very quickly becoming easily ignitable. Because of this, these fuels can become dry over the course of an abnormally dry and hot day. Then with the added effect of them being thermally thin makes them easier to heat and ignite.

For forest fires, however, the major fuel first ignited is "heavy vegetation, including trees," corresponding to 44% of these fires (Balch et al. 2017). The difference of this is attributed to two

factors: firstly lightning is a more frequent cause of forest fires due to their height of large trees relative to smaller vegetation. Secondly the forest canopy limits the amount of sunlight reaching the finer fuels that are present on the forest floor, limiting their ability to dry as much as if they were exposed to direct sunlight.

Structure Fuels

In WUI fires, man-made structures can be found on the interface with wildland areas. The structures can be ignited from traditional flame spread (flame contact) or flame radiation but also by firebrand spotting. Firebrand spotting is the process by which burning materials are moved significant distances by the wind and/or fire-induced gas dynamics. Recent studies estimate firebrand spotting to be the largest cause of structure loss in WUI fires as compared to direct flame contact or radiation from flames (Maranghides and Mell 2013; Mell et al. 2010). A recent review article (Caton et al. 2016) provides an overview of several components of structures that have been identified as vulnerabilities from firebrand spotting, flame contact, and flame radiation. Specifically mentioned are roofing, gutters, eaves, vents, siding, windows, glazing, decks, porches, patios, fences, mulches, and debris (Caton et al. 2016). These vulnerable components themselves can serve as the fuel itself, they can serve as a place for fuels to collect such as leaf or pine litter from nearby trees collecting on roofs, patios/decks, and gutters), and they can also provide a path for embers to enter the interior of the home (vents, open windows).

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The potential materials to be ignited first in structures are consequently much more diverse as they encompass natural fuels such as pine and leaf litter accumulated on the house, synthetic fuels such as roofing material and siding material, and minimally processed biomass-derived fuels such as decking. These fuels also span the range from very fine fuels (pine and leaf litter) to larger wood components (decking). Large wood components have low porosity (small void fraction) and typically require more heat to ignite. Consequently, these larger materials require more significant flame interactions and/or accumulation of embers to overcome the demand imposed by the larger energy requirements compared to the finer fuels.

Ignition Process

The differences in common fuels first ignited in wildland and WUI fires also cause differences in ignition pathways. The finer, natural fuels can be ignited more easily, by a single firebrand (Manzello et al. 2006, 2008) or a relatively small amount of flame contact or radiation, and the larger fuels such as wood components (e.g., decking) require significantly more energy deposition to ignite which comes in the form of accumulations of many firebrands which combined can ignite these much larger pieces. The ember accumulations occur due to surface roughness and local flow structures near fuels (Suzuki and Manzello 2017). Smaller natural fuels can act as tinder and kindling to ignite the larger fuels. The ignition of the larger fuels can also be made easier by reducing heat losses; examples of this are ignition of gaps in decking and crevices which provide opportunities for reradiation.

Ignition of Wildland Fuels

Wildland fuels have a morphology that is very different from that of a continuous solid. Typically, surface fuels consist of fine, solid pieces of biomass, arranged to form a heterogeneous porous material. The morphology of the fuel could vary from powder and very thin pieces (duff, grass, etc.) to relatively larger pieces of woody material (needles, twigs, branches, etc.). The canopy fuels are also composed of thin pieces (leaves, needles, etc.) to large woody materials (branches, trunks, etc.). Also, the fuel could be dry, moist, or live. Consequently, the ignition and burning characteristics of these fuels are much more complex than that of a continuous solid fuel such as a slab of wood or plastic. Furthermore, in addition to flaming ignition of the fuel, the porous character surface fuels also allow the onset of smolder ignition, thus introducing a wide range of potential ignition modes, from smolder to spontaneous and piloted ignition

(Drysdale 2011). Finally, the morphology of the fuel allows for a wide range of ignition sources, from an open flame or hot surface to embers and hot metal particles.

When surface wildland fires are first ignited, the fuel bed is typically composed of layers of fine fuels such as pine needle litter, leaf litter, or dry grass (Ahrens 2013). These fuel beds typically have large void fractions, ϕ, (fraction of fuel bed volume occupied by air), and since biomass and air have low thermal conductivity, these porous fuels are characterized by low thermal conductivities. Consequently, wildland fuel beds would have a large Biot numbers, ($Bi > 0.1$), and they would be considered to be thermally thick following the definition that the heated layer would be smaller than the fuel thickness. The Biot number is the ratio of internal conductive thermal resistance to external convective thermal resistance at the surface, given by the equation $Bi = hL/k$ where h is the convection coefficient, L is the characteristic thermal length scale, and k is the thermal conductivity of the solid. However, when heated by an external source, only a relatively thin outer layer of the fuel would be heated ~~up~~, and the fuel would behave as a thin fuel in some aspects of the problem. The fuels in this layer would reach their pyrolysis temperature much faster than if they were nonporous, while the rest of the fuel underneath the layer would heat up more slowly. Thus, although the wildland fuel bed would be theoretically thermally thick, in practice it would behave as thermally thin ($Bi < 0.1$), in the sense that only a thin surface layer of the fuel bed would heat up. How fast it would heat up would depend on the heating source and the morphology characteristics of the fuel bed. In addition of the complexity that the fuel bed morphology brings, wildland fuels contain moisture, so the heating and evaporation of the moisture complicate the ignition process further. The moisture is primarily water, especially in the case of dead biomass fuels, although recent studies have shown that the drying behavior can be more complex with live fuels (Mcallister and Weise 2017).

Ignition of Structure Materials

The ignition of a structure is more difficult than the ignition of a wildland fuel: structure fuels are much denser, with higher thermal conductivities, and consequently required more energy and time to be ignited. While studies have shown that duff, litter, mulch, and other fine fuels can be ignited by single firebrands, larger solid structures require accumulations of many firebrands to ignite the structure. An alternative ignition pathway would be to ignite accumulated fine natural fuels on or near the structure which act as tinder and kindling, igniting first then igniting the larger fuel (Manzello et al. 2010, 2017; Cohen and Stratton 2008). The ignition of the larger fuels can also be made possible by reducing heat losses; examples of this are ignition of gaps in decks (Manzello and Suzuki 2014), and crevices (Manzello et al. 2009) by firebrands by creating opportunities for reradiation. Structure fuels are also typically thermally thick like wildland fuels, but do not have the same porous nature. This means that while similar equations can be used to describe the ignition process, the requirements for ignition are higher: the fuels require more heating, over a longer time to ignite compared to a wildland fuel.

Formulation of the Ignition Problem

A rigorous analysis of the ignition of a fuel requires the solution of the full conservation equations for the solid and gas phases. As mentioned above this is quite complex, although some simplifying assumptions can be made to make the problem formulation and solution more manageable. Furthermore, the heterogeneous characteristics of the fuel bed can be simplified by assuming that it behaves as a homogeneous porous material. Considering the fuel as 1-D and homogeneous, the energy equation can be expressed as

$$\rho_f (1-\phi) c_f \frac{dT}{dt} = k_{eff} \frac{d^2T}{dx^2} + \dot{\omega}'''_{p,ex} \Delta h_{p,ex} - \dot{\omega}'''_{p,en} \Delta h_{p,en} - \dot{\omega}'''_{dry} \Delta h_{vap} \quad (1)$$

The term on the left-hand side of Eq. 1 is the energy storage term, the first term on the right-hand side accounts for thermal diffusion, and the remaining terms are the rates of the oxidative and thermal pyrolysis reactions and the evaporation reaction. Here ϕ, c_f, and ρ_f are the porosity, specific heat capacity, and density of the fuel; $k_{eff} = k_f + \gamma(\phi)\sigma T^3$ is the effective conductivity of the fuel accounting for the true conductivity of the fuel and the effective pore-radiation thermal conductivity if the porosity is large enough that pore/gap radiation is important. In the case of a nonporous fuel, ϕ would have a value of 0, whereas for wildland fuels such as accumulated fine fuels, the porosity would be non-zero. The generalized boundary conditions for Eq. 1 are given by Eqs. 2 and 3 for the interaction of the fuel boundary with the ignition source and the ambient surroundings and the fact that the fuels are thermally thick and heat transfer far from the heated boundary is minimal, respectively.

$$-\rho_f k_{eff} \left.\frac{dT}{dx}\right|_{surf} = h_{conv}\left(T_{surf} - T_\infty\right) + \epsilon\sigma\left(T_{surf}^4 - T_{rad}^4\right) \tag{2}$$

$$\left.\frac{dT}{dx}\right|_{x\to\infty} \to 0 \tag{3}$$

In the solid fuel, the material must be heated to the point at which pyrolysis reactions will occur producing enough pyrolyzate to support combustion. The pyrolysis of biomass can be complicated with several intermediate pyrolysis steps (Lautenberger and Fernandez-Pello 2008). In general, there are two main pyrolysis pathways: endothermic pyrolysis reactions and exothermic oxidative pyrolysis reactions. For flaming ignition, it is typically assumed that the pyrolysis reactions act as a net heat sink, but for smoldering ignition the oxidative surface reactions must be strong enough so that they produce enough heat to offset any heat losses. Thus, the oxidative pyrolysis term, $\dot{\omega}'''_{p,ex}\Delta h_{p,ex}$, would typically play a larger role in smoldering ignition than for flaming ignition and would need to produce enough heat for the smolder to propagate. The fuel moisture can play an important role in the fuel bed ignition, deterring it because of the energy required to vaporize the water.

In its simplest form, the fuel pyrolysis reaction can be described by a single, first-order in fuel, Arrhenius-type reaction. The rate of pyrolysis is then given by the equation

$$\begin{aligned}\dot{m}''_{pyr} &= \int_0^{\delta_{pyr}} \sum_{i=0} \alpha_i \dot{\omega}_i''' dx \\ &= \int_0^{\delta_{pyr}} \sum_{i=0} \alpha_i \rho_f (1-\phi) A_i \\ &\quad \exp\left(-\frac{E_{a,i}}{RT}\right) X_{O_2}{}^{n_{O_2}} dx\end{aligned} \tag{4}$$

where δ_{pyr} is the region of the solid fuel that is undergoing pyrolysis and α_i is the amount of pyrolyzate fuel produced per amount of solid fuel pyrolyzed. The endothermic vaporization term would have similar formulation. It should be noted here that the value of the porosity will have strong implications on the reaction kinetics and thus parameters such as A_i and $E_{a,i}$ could change if the porosity were changed.

An important result of Eq. 4 is that since wood has a relatively large activation energy, the rate of pyrolysis is strongly dependent on the fuel temperature. Consequently, the rate of pyrolysis is small until a certain temperature, T_p, is reached, referred to as the pyrolysis temperature. The strong temperature dependence of the pyrolysis makes the rate of gasification influenced by the heat input from the external source or exothermic pyrolysis reaction. So, if the fuel is heated to the pyrolysis temperature, and in the presence of sufficient oxygen, a strong ignition source (pilot), and appropriate ambient conditions, ignition will occur. Thus, this temperature can be viewed as an "ignition" temperature, T_{ign}. While this approach is sufficient for practical purposes, changes in the other parameters (i.e., oxygen supply, external heating, characteristics of the ignition source, and ambient conditions) could require higher temper-

atures for ignition. Thus, the ignition temperature should be treated as a useful engineering concept but not a fundamental material property.

The solution of Eq. 1 gives the variation with time of the fuel bed temperature along the fuel layer depth. As mentioned above the solution is not simple. However, assuming the fuel starts to pyrolyze once the fuel reaches the pyrolysis temperature, and that there is enough heat input for the fuel to pyrolyze and form a flammable mixture with the air near the fuel surface, in the presence of a strong pilot, flaming ignition would occur. The formulation of the problem can then be simplified to the point that an analytical expression can be obtained for the temperature of the fuel bed and the time required for ignition. In a phenomenological manner, the solid fuel ignition process can be described as follows: the solid fuel sample, considered initially at ambient temperature, T_∞, is suddenly exposed to an incident heat flux (q''_{ext}) from an external source. The temperature of the solid rises until the surface reaches the temperature at which the fuel first pyrolyzes, T_p, at which point the fuel ignites.

The energy required to ignite the fuel can be expressed as

$$E_{ign} \approx \int_{\delta} A\rho_f (1-\phi) c_f \left(T_p - T_0\right) dx + \int_{\delta} A\rho_f (1-\phi) FMC\, \Delta h_{vap.} dx + \int_0^{t_{ign}} \int_{\delta} A \left(\dot{\omega}'''_{p,en} \Delta h_{p,en} - \dot{\omega}'''_{p,ex} \Delta h_{p,ex}\right) dx dt + \int_0^{t_{ign}} A \left(h_{conv} \left(T_{surf} - T_\infty\right) + \epsilon\sigma T_{surf}^4 - q''_{ext}\right) dt + E_{gas} \tag{5}$$

where δ is the thickness of the thin layer on the surface of the sample that is significantly, heated, dried, and pyrolyzed. Here A is the fuel exposed to the heat source and E_{gas} is the energy needed to ignite the gas phase fuel/air mixture.

The time required for the fuel surface to attain T_p will be referred to as the pyrolysis time, t_p. After attaining T_p, increasing amounts of fuel vapors (pyrolysate) leave the surface, through diffusion or convection away from the sample, and subsequently mix with the ambient air and create a flammable mixture near the solid surface. This period will be referred to here as the mixing time (t_m). The external flux, fuel properties, oxidizer flow, and geometrical characteristics determine the mixing time and a characteristic surface mixing temperature, T_m, at the end of this mixing period; if the mixture temperature is increased by a pilot or other mechanisms, a combustion reaction between the fuel and the air may become vigorous enough to overcome the heat losses to the solid and ambient surroundings, thereby becoming self-sustaining, at which point ignition will occur. This the time over which the reaction happens is called the induction time (t_{ind}) and is determined by combustion chemical kinetics as well as the flow and pilot conditions. The ignition delay time (t_{ign}) can then be described by

$$t_{ign} \approx t_p + t_m + t_{ind} \tag{6}$$

In general, the pyrolysis time of solid fuels, t_p, is much larger than the mixing and induction time. Thus, ignition time becomes the same as the pyrolysis time, which is given by the solution of the inert version of Eq. 1, i.e., the heat equation for a thermally thick fuel. Then the ignition time is given by

$$t_{ign} = \frac{\pi}{4} k_f c_f (1-\phi) \rho_f \frac{\left(T_{ign} - T_0\right)^2}{\left(\dot{q}''_s\right)^2} \tag{7}$$

where $\dot{q}''_s$ is the net heat flux at the surface of the fuel.

By examining Eqs. 1 and 7, it is seen that as the porosity is increased, the energy required for ignition and the time for ignition decrease. Also, since the density and thermal conductivity of the fuel bed are small, the ignition time is also small. These are very specific ignition characteristics of

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replace with: "particles"

wildland fuel beds that make them particularly hazardous in comparison with other solid combustible materials.

Regarding the "ignition temperature," $T_{ign} \sim T_p$, its value is dependent on the method by which the fuel is ignited and the environment conditions. The literature has studies on several ignition scenarios such as a hot plate at a fixed temperature (Pitts 2007) thermal radiation (Torero and Simeoni 2010), convection (McAllister and Finney 2017; McAllister and Finney 2014), and hot metal ~~particle~~ or glowing/burning embers (Urban et al. 2016, 2018; Fernandez-Pello et al. 2014; Manzello et al. 2006). In the case of radiantly ignited pine needles, an ignition temperature of 412 °C was determined although it was dependent on the convective heat losses to the ambient surroundings (J. L. Torero and Simeoni 2010). For the ignition of pine needles with a hot flat surface, a hot plate temperature of 310 °C without wind and up to 320 °C at low wind speeds were reported (Pitts 2007). In the case of ignition of a fuel by embers or firebrands, the requirements for ignition can be more difficult because as the ember burns out, the energy transferred to the fuel bed decreases. For hot metal particles/sparks landing on the fuel bed, the particle loses energy as it heats the fuel, and depending on its energy and temperature, it may, or may not, be able to ignite the fuel. For this reason, the particle temperature and size (energy) at landing on the fuel bed are important in determining the ignition capability of the particle. For different types of fuel beds, it has been found that there is an inverse relationship between particle temperature and size for the particle to ignite the wildland fuel, with the temperature increasing as the size of the particle decreases (Fernandez-Pello et al. 2014).

Conclusions

In wildland and WUI environments, wildland surface fuels (duff, needles, grass, etc.) are easy to ignite by short flame contact, radiation, or even individual embers. Consequently, flames will spread very fast along their surface, which make them very hazardous. This is because the fuel beds are porous, with large void fraction, and have low density and thermal conductivity, and when exposed to an external heat source, the heat is retained in a thin layer near the surface. Typically, the fuels in the surface layer are mostly dead, and in hot, dry days, the fuel temperature increases rapidly resulting in short ignition times and rapid flame spread. Similar fire conditions occur in dense tree canopies, although if the fuel (leaves, pine needles) is live, the ignition process may be more complex than with dead fuels. Structure fuels are much larger and require larger sources of heat such as longer flame or radiation contact or accumulations of firebrands/embers, unlike the finer porous fuels, or they must be ignited from adjacent accumulations of fine fuels such as pine needles and leaves. Despite the differences in their energy and heating requirements, they, both accumulations of fine natural fuels and larger fuels found in structures, can often behave as thermally thick fuels.

Predicting the ignition of fuels in the wildland and WUI is difficult because of the complexity and varieties of the fuels. The wildland fuel beds have a varied morphology (from powders to thick branches), porous with a heterogeneous structure, moisture levels that change with the ambient conditions, and dead and live fuels. Structure fuels are more difficult to ignite, and the ignition process becomes dependent on the ability to ignite a comparatively large, dense fuel by either igniting kindling/tinder first, substantial ember accumulations, and/or reradiation to reduce heat losses. This reduces the possibility of assigning a value to an "ignition temperature" to fuels, thus limiting the application of simplified analysis of the wildland and structure fuel ignition (including the analysis presented here). Thus, when evaluating the ignition of a fuel, aspects of the problem beyond the characteristics of the fuel must also be considered such as the environmental parameters (i.e., humidity, wind speed, ambient temperature, etc.), the ignition source (e.g., radiant heater, hot object/surface, burning firebrand/ember, flame contact lightening, etc.), as well as the natural variations that exist in biomass fuels.

Cross-References

- Combustion
- Conduction
- Convection
- Data on Wildland Ignition Sources
- Direct Flame Contact
- Firebrands and Embers
- Radiant Heat
- Radiation Pyrolysis

Nomenclature

FMC	Fuel moisture content $FMC = \frac{m_{\text{moisture}}}{m_{\text{dry fuel}}}$
ϕ	Void fraction
A	Area
c_f	Specific heat capacity of the solid
ρ_f	Density of solid fuel
$\dot{\omega}'''_{p,i}$	Rate of consumption by ith pyrolysis reaction
$\Delta h_{p,\,i}$	Energy absorbed or released by ith pyrolysis reaction

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