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Abstract

A simple theory on fuel ignition by firebrands was developed based on the ignition criteria of the Semenov thermal theory. Two dimensionless parameters were identified and used to demarcate the ignition and non-ignition regions in an ignition regime map. The parameters from the ignition and non-ignition states were used as input to numerically solve the governing energy balance to obtain the dimensionless transient temperature profile in the fuel layer, which was used to verify if ignition or thermal runaway occurred and to determine dimensionless ignition time.

Keywords

Dimensionless parameters; firebrand; heat transfer; ignition; wildfires

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Author Contributions

Author 1: Conceptualization, Methodology, Writing - Original draft preparation, Editing. **Author 2**: Writing - Reviewing and Editing.

1. Introduction

Each year, tens of thousands of wildfires burn globally. These wildfires destroy structures and wildland vegetation. Wildfires spread through three different mechanisms: radiation, direct flame contact, and spotting ignition due to firebrands. The ability of a firebrand or pile of firebrands to ignite a substrate fuel is dependent on the energy contained within the firebrand, environmental conditions, and the substrate properties. One way to study the ignition of fuel substrates by firebrands is the application of hot-spot ignition theory. In this sense, firebrands are acting as the heat source or "hot spots" for ignition in a localized region of the substrate. Thomas [1] provided an overview and comparison of various hot-spot theories. Applying some form of hot-spot theory, Jones [2,3,4,5] performed calculations to predict the effects of an accidental heat source on a previously thermally inactive bed of forest litter. Hadden et al. [6] utilized hot-spot ignition theory for the particle size-temperature relations for ignition. This paper is an attempt to develop a non-dimensional ignition regime map for firebrands on a fuel substrate using simplified ignition criteria. The dimensionless parameters were identified by following similar procedures used in the hot-spot ignition theories.

2. Analysis

Figure 1 shows the schematic diagram illustrating the heat transfer processes in the ignition of a fuel layer by firebrands.

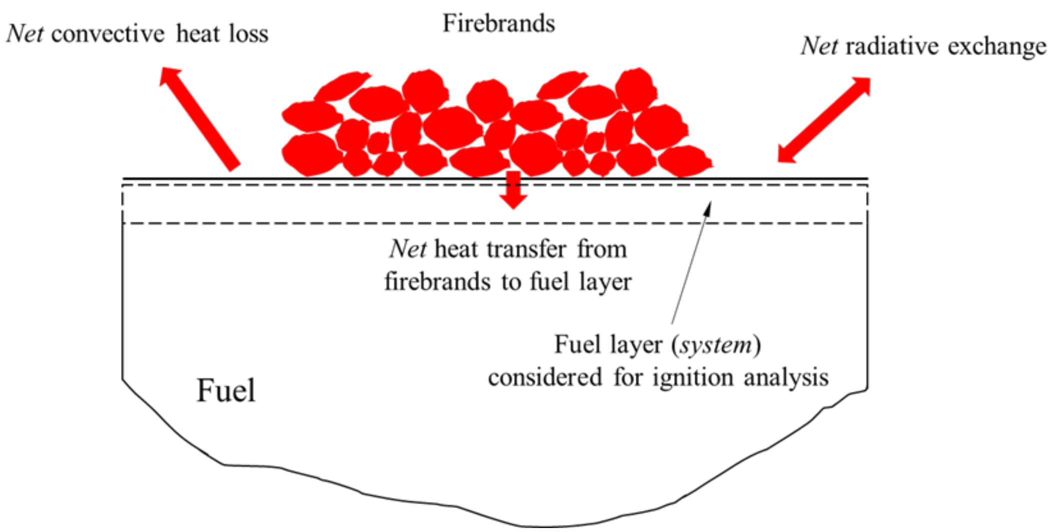

Fig. 1. The heat transfer processes in the ignition of a fuel layer by firebrands.

The system considered is a thin fuel layer with spatial uniform system temperature. There is a chemical reaction in the fuel layer, and ignition happens when there is a thermal runaway of the chemical reaction. An energy balance on the fuel layer gives:

$$\rho V c_p \frac{dT}{dt} = \dot{Q}_f - r_A V \Delta_c H_{fuel} - hA(T - T_\infty) - A\varepsilon_r \sigma(T^4 - T_\infty^4) \qquad (1)$$

In Eq. (1), the second term is the net heat transfer from the firebrands to the fuel, the third term is the energy generated due to chemical reaction in the fuel layer, the fourth term is the convective heat loss from the fuel surface, and the fifth term is the radiative heat exchange between the exposed fuel surface and the surroundings. When the fuel cannot be considered as thermally thin, we could still treat a thin layer of fuel where it plays a critical role in ignition. In addition, the in-depth heat conduction in the fuel is neglected, implying the characteristic ignition time (t_{ig}) is much shorter than the heat conduction time ($t_{ig} << \delta^2 / \alpha$). Implicit in Eq. 1 is the assumption that $A_c << A$. Radiative transfer from the firebrands to the fuel surface and convective heat loss from the firebrands are lumped into $\dot{Q}_f$. That is, $\dot{Q}_f$ is considered the net heat transfer rate to the fuel from the firebrands. For this simplified analysis and noting that the heat flux from a firebrand is transient in nature, we assume $\dot{Q}_f \neq \dot{Q}_f\cancel{(t)}$ and $\dot{Q}_f \approx$ constant.

From Carslaw and Jaeger [7], the following linearized approximation may be applied to the radiative term, assuming $(T - T_\infty)$ is not large before ignition.

$$\varepsilon_r \sigma (T^4 - T_\infty^4) \approx \varepsilon_r \sigma T_\infty^3 (T - T_\infty) \tag{2}$$

Substituting Eq. (2) into Eq. (1),

$$\rho V c_p \frac{dT}{dt} = \dot{Q}_f - r_A V \Delta_c H_{fuel} - \tilde{h} A (T - T_\infty) \tag{3}$$

where $\tilde{h} \equiv h + \varepsilon_r \sigma T_\infty^3$.

For now, a zero-order chemical reaction rate for the fuel substrate is assumed,

$$-r_A = \mathscr{A}_0 \exp(-\frac{E_0}{RT}) \tag{4}$$

Note that a first-order chemical reaction rate can be assumed; however, if the fuel consumption rate is assumed to be negligible before ignition, the fuel concentration is relatively constant and can be lumped into the frequency factor of the rate equation making it a pseudo zero-order rate equation.

Substituting Eq. (4) into Eq. (3),

$$\rho V c_p \frac{dT}{dt} = \dot{Q}_f + \mathscr{A}_0 \exp(-\frac{E_0}{RT}) V \Delta_c H_{fuel} - \tilde{h} A (T - T_\infty) \tag{5}$$

Define

$$\theta \equiv \frac{E_0}{R T_\infty^2} (T - T_\infty) \tag{6}$$

Jones [8] shows that

$$\exp(-\frac{E_0}{RT}) = \exp(\frac{\theta}{1 + \varepsilon\theta}) \exp(-\frac{E_0}{R T_\infty}) \tag{7}$$

where $\varepsilon \equiv \dfrac{R T_\infty}{E_0}$.

Since $\varepsilon << 1$ usually, we have $1 + \varepsilon\theta \approx 1$.

Equation (7) then becomes

$$\exp(-\frac{E_0}{RT}) = \exp(\theta)\exp(-\frac{E_0}{RT_\infty}) \tag{8}$$

Substituting Eq. (6) and Eq. (8) into Eq. (5), we obtain

$$\frac{d\theta}{d\tau} = \Omega + \exp(\theta) - \hat{h}\,\theta \tag{9}$$

where

$$\tau \equiv \frac{\mathcal{A}_0 E_0 \Delta_c H_{fuel}}{\rho c_p R T_\infty^2}\exp(-\frac{E_0}{RT_\infty})\, t \tag{10}$$

$$\hat{h} \equiv \frac{\tilde{h} A R T_\infty^2}{\mathcal{A}_0 E_0 V \Delta_c H_{fuel}}\exp(\frac{E_0}{RT_\infty}) \tag{11}$$

$$\Omega \equiv \frac{\dot{Q}_f}{\mathcal{A}_0 V \Delta_c H_{fuel}}\exp(\frac{E_0}{RT_\infty}) \tag{12}$$

From Eq. (9), the two thermal ignition criteria based on the Semenov model [9], which calls for the balance of heat gain and heat loss, Eq. (13), and the balance of the rate of change of heat gain and that of heat loss with respect to the system temperature, Eq. (14), are applied:

$$\Omega + \exp(\theta_{ig}) = \hat{h}\,\theta_{ig} \tag{13}$$

$$\frac{d}{d\theta}\left[\Omega + \exp(\theta)\right]\Big|_{\theta=\theta_{ig}} = \frac{d}{d\theta}\left(\hat{h}\,\theta\right)\Big|_{\theta=\theta_{ig}} \tag{14}$$

Since $\Omega \neq \Omega(\theta)$ and $\hat{h} \neq \hat{h}(\theta)$, Eq. (14) becomes

$$\exp(\theta_{ig}) = \hat{h} \tag{15}$$

Substituting Eq. (15) into Eq. (13),

$$\theta_{ig} = \frac{\Omega + \hat{h}}{\hat{h}} = \frac{\Omega}{\hat{h}} + 1 \tag{16}$$

For a given θ_{ig} and $\hat{h}$, the critical Ω_{ig} for ignition by firebrands can be viewed as

$$\Omega_{ig} = \theta_{ig}\hat{h} - \hat{h} \tag{17}$$

Substituting Eq. (15) into Eq. (17),

$$\Omega_{ig} = \hat{h}\left[\ln(\hat{h}) - 1\right] \tag{18}$$

One could argue if $\Omega > \Omega_{ig}$, then the energy from firebrands will ignite the fuel bed.

Since $\Omega_{ig} \geq 0$, $\hat{h}\left[\ln(\hat{h}) - 1\right] \geq 0$, and $\ln(\hat{h}) \geq 1$,

$$\hat{h} \geq e(\approx 2.7183) \tag{19}$$

Hence, the two dimensionless parameters governing the ignition process are $\hat{h}$ and Ω, which can be used to construct an ignition regime map.

3. Results and Discussion

Figure 2 shows the fuel ignition regime map plotted as $\Omega = \Omega(\hat{h})$ based on the Semenov thermal ignition theory. The two dimensionless parameters, $\hat{h}$ and Ω, demarcate the ignition and non-ignition regions. This map provides the criteria to determine the necessary $(\hat{h},\Omega)$ for ignition to occur. Figure 2 also shows that for non-ignition events, a minimum of $\hat{h} = 2.7183$ is required based on the analysis. For $\hat{h} < 2.7183$, any $\Omega > 0$ would result in ignition.

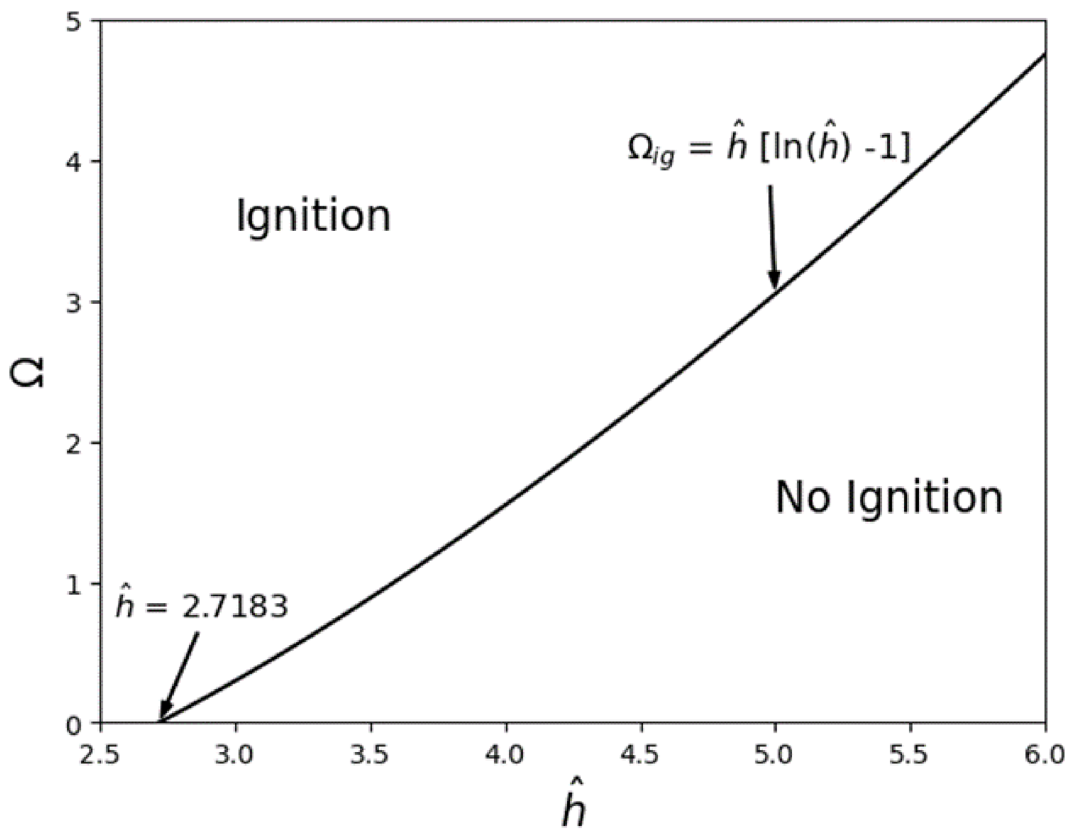

Fig. 2. Fuel ignition regime map obtained using the Semenov thermal ignition theory.

Various $(\hat{h},\Omega)$ pairs from both ignition and non-ignition states were used as input parameters to numerically solve the governing unsteady energy balance, Eq. (9), to obtain the dimensionless transient temperature profile in the fuel layer, which was used to verify if ignition or non-ignition occurred and to determine dimensionless ignition time if ignition occurred.

Figure 3 shows the dimensionless temperature of the fuel layer as a function of dimensionless time for various ignition cases based on various $(\hat{h},\Omega)$ pairs in the ignition region of Fig. 2. The dimensionless ignition times (defined as the τ where θ increases exponentially indicating thermal run-away or ignition) for these three cases are $\tau_{ig} \approx 0.8$, $\tau_{ig} \approx 0.9$, and $\tau_{ig} \approx 1.0$ respectively.

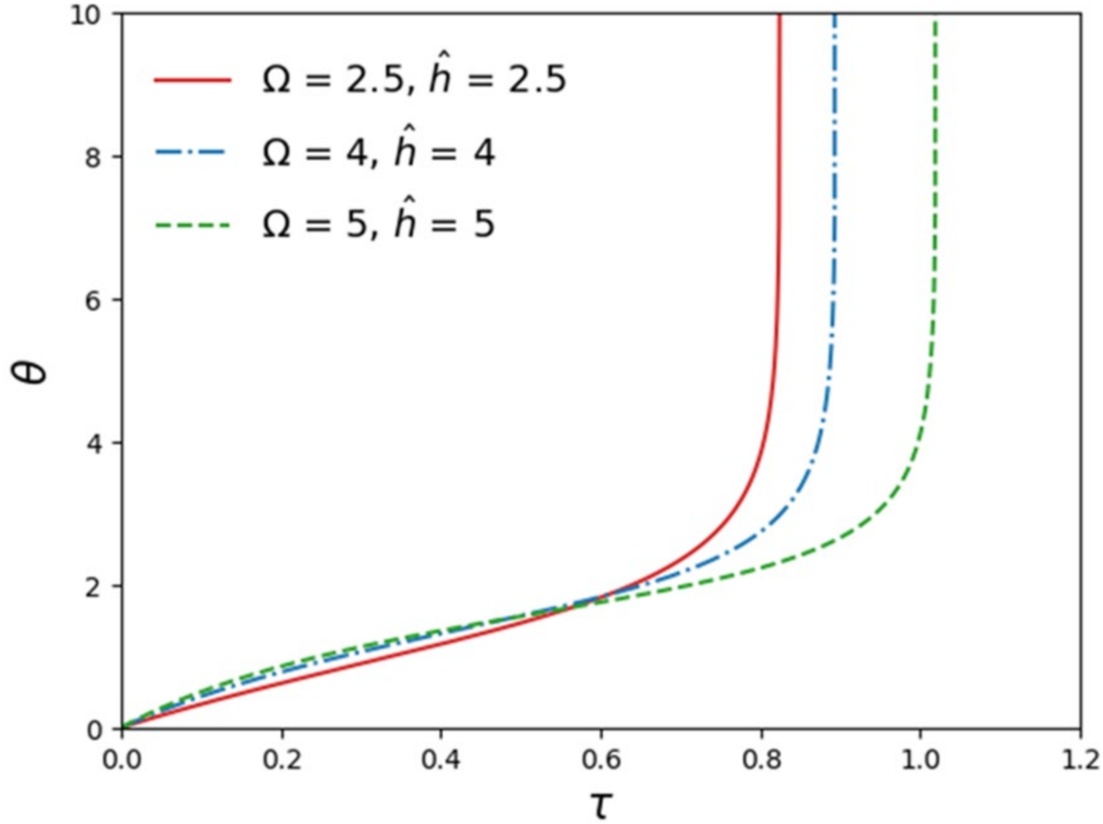

Fig. 3. Various ignition cases based on various $\hat{h}$ and Ω in the ignition region of Fig. 2.

Figure 4 shows the dimensionless temperature of the fuel layer as a function of dimensionless time for various non-ignition cases based on various $(\hat{h} = 5, \Omega)$ pairs in the non-ignition region of Fig. 2. Note that there is no ignition, and θ is approaching asymptotically a steady-state value as $\tau \to \infty$. For a given $\hat{h}$, increasing Ω increases θ at a given τ. As Ω increases, the steady-state value of θ approaches its asymptote later.

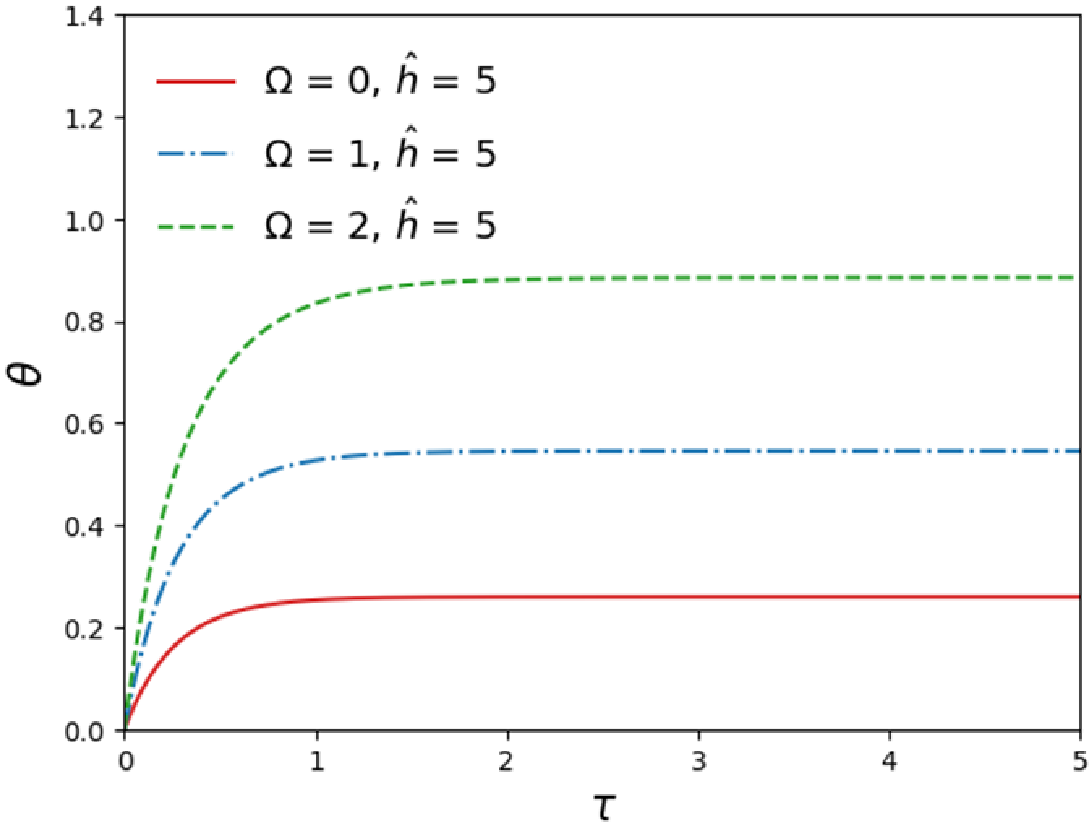

Fig. 4. Various non-ignition cases based on $\hat{h} = 5$ and various Ω in the non-ignition region of Fig. 2.

Figure 5 shows the dimensionless temperature of the fuel layer as a function of dimensionless time for various ignition and non-ignition cases based on various $(\hat{h}, \Omega = 1)$ pairs in the ignition and non-ignition regions of Fig. 2. For a given Ω, increasing $\hat{h}$ delays the thermal run-away or ignition; however, further increase in $\hat{h}$ would result in non-ignition event, in this case $(\hat{h} = 5, \Omega = 1)$ which is in the non-ignition region of Fig. 2.

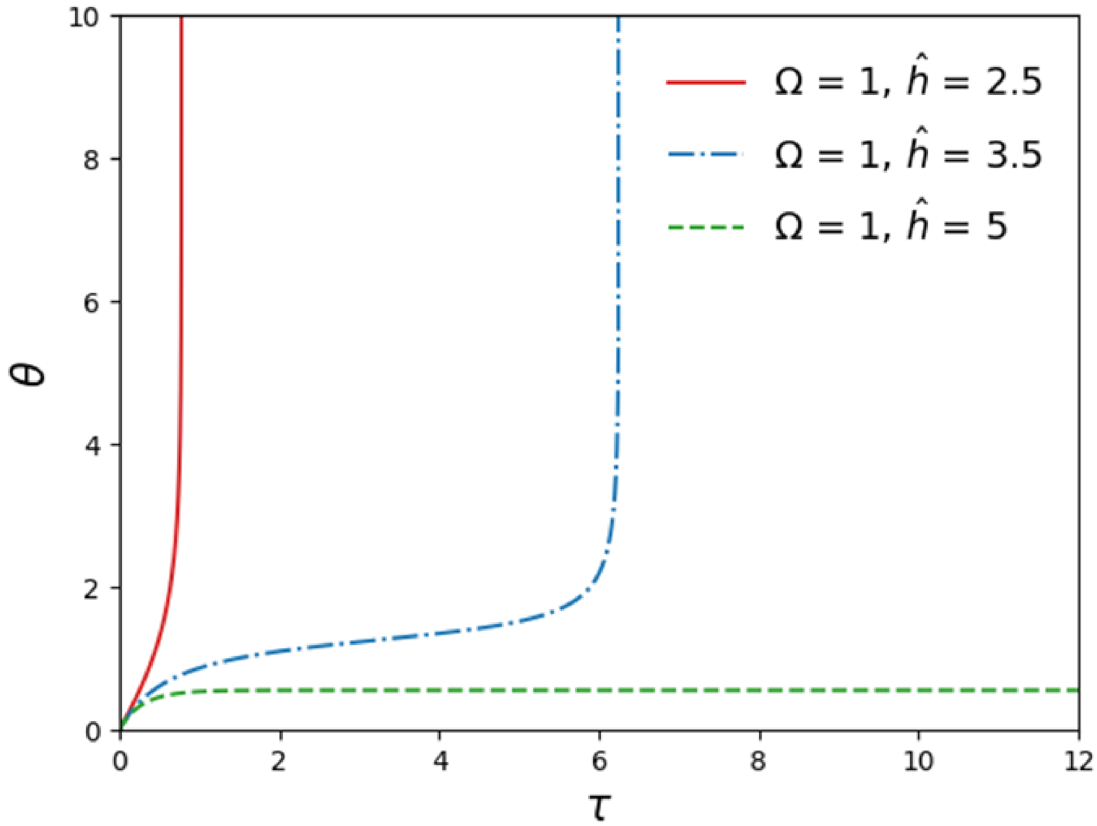

Fig. 5. Various ignition and non-ignition cases based on various $\hat{h}$ and $\Omega = 1$ from Fig. 2.

4. Conclusions

A simple model on a fuel layer ignition by firebrands was developed based on the Semenov thermal ignition criteria. Two dimensionless parameters were identified and used to demarcate the ignition and non-ignition regions in an ignition regime map. The two parameters were used to numerically solve the governing energy balance equation to verify the ignition state and to determine the dimensionless ignition time. The two dimensionless parameters from the simple analysis could provide a useful basis for correlating experimental data on fuel ignition by firebrands.

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Appendix A. List of Symbols, Abbreviations, and Acronyms

$\boldsymbol{A}$
Exposed fuel surface area (m^2)

$\boldsymbol{A}_c$
Contact area between firebrands and fuel (m^2)

$\mathcal{A}_0$
Frequency factor (mol s^{-1} m^{-3})

$\boldsymbol{c}_p$
Fuel specific heat (J mol^{-1} K^{-1})

$\boldsymbol{E}_0$
Activation energy of reaction (J mol^{-1})

$\boldsymbol{h}$
Convective heat transfer coefficient (J s^{-1} m^{-2} K^{-1})

$\tilde{\boldsymbol{h}}$
Pseudo convective heat transfer coefficient $(\equiv h + \varepsilon_r \sigma T_\infty^3)$

$\hat{\boldsymbol{h}}$
Dimensionless heat transfer coefficient, defined by Eq. (11)

$\Delta_c \boldsymbol{H}_{fuel}$
Heat of combustion of fuel (J mol^{-1})

$\dot{\boldsymbol{Q}}_f$
Heat transfer rate from firebrands to fuel (J s^{-1})

$\boldsymbol{r}_A$
Reaction rate of fuel (mol s^{-1} m^{-3})

$\boldsymbol{R}$
Universal gas constant (J mol^{-1} K^{-1})

$\boldsymbol{t}$
Time (s)

$\boldsymbol{T}$
Fuel temperature (K)

$\boldsymbol{T}_\infty$
Surrounding temperature (K)

$\boldsymbol{V}$
Fuel layer volume (m^3)

$(\cdots)$
As a function of $\cdots$

Greek symbols

$\boldsymbol{\alpha}$
Fuel thermal diffusivity (m^2 s^{-1})

ε
Dimensionless parameter ($\equiv (RT_\infty)\,/\,E_0$))

ε_r
Fuel emissivity (--)

$\boldsymbol{\delta}$
Fuel layer considered for ignition (m^3)

$\boldsymbol{\theta}$
Dimensionless temperature ($\equiv E_0(T - T_\infty)\,/\,(RT_\infty^2)$)

$\boldsymbol{\rho}$
Fuel density (mol m^{-3})

$\boldsymbol{\sigma}$
Stefan-Boltzmann constant (J s^{-1} m^{-2} K^{-4})

$\boldsymbol{\tau}$
Dimensionless time, defined by Eq. (10)

$\boldsymbol{\Omega}$
Dimensionless heat transfer rate from firebrands, defined by Eq. (12)