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Downward flame spread along a single pine needle: Numerical modelling

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ABSTRACT

In this work downward flame spread over single pine needle of *Pinus Sibirica* is studied. Pine needles are thin cellulosic charring combustible forest fuel elements. Idealising pine needles to thin cylinders, a 2D axisymmetric numerical model is developed accounting for char formation and char oxidation to investigate the important mechanisms which control the downward spread of flame over a pine needle in normal gravity, atmospheric condition and at various opposed flow conditions. Simultaneous formation of char and pyrolysate during the pyrolysis process was found to significantly reduce the flame spread rate over thin fuel. Presence of char resulted in change in distribution of fuel vapour mass flux above the fuel surface which led to decrease in forward heat feedback to the fuel and hence the flame spread rate. This mechanism is different from char acting as a thermal barrier to heat transfer from the flame in case of thick fuel. Char oxidation had no influence on flame spread rate as char oxidation was found to occur only after passage of flame with the availability of surrounding oxygen diffusing through the hot plume of combustion products. Char oxidation was primarily controlled by oxygen diffusion rate to the charred fuel surface. The flame spread data for quiescent flame spread, and the blow off opposed flow velocity was used to calibrate gas phase kinetics and pyrolysis kinetics. The model predicted flame spread rate variation with opposed flow velocity quite well. The predicted spatial distribution of temperature and species concentration also compared very well with the experimentally determined flame structure.

1. Introduction

The study of fire propagation in forest fuels is important because of the inherent risk of the potential fire hazard. It is imperative to have a better understanding on how flame spreads over forest fuel so as to contribute to the progress in fire safety research. The critical condition for fire propagation depends on the individual fuel element [1] especially thin components like leaves or the foliage. Therefore, studying the combustion and flame spread mechanism of a single pine needle (SPN), which is one of the most combustible components of forest fuel, will help in understanding the mechanism of flame spread over thin charring solid fuels and ground fire spread.

Flame spread over charring fuels has been studied primarily for thick fuels and study of flame spread over thin charring fuels has received comparatively little attention. A flame spread study over a solid fuel slab by Carrier et al. [2] modelled degradation of the fuel into only pyrolysate, and later incorporated char formation along with pyrolysate in the model, [3]. The study [3] showed that the char layer plays a significant role in thermal resistance, heat retention and solid surface emission. In a study by Wichman and Atreya [4] a simplified model of pyrolysis of thick charring materials identified four stages of pyrolysis namely, inert heating, initial pyrolysis, thin char, and thick char. Study showed that the surface temperature controls the volatile production rate at the initial pyrolysis stages (the kinetically controlled regime), while the temperature gradient controls the volatile production rate at the thick char stage (the diffusion-controlled regime). In the numerical studies of Di Blasi et al. [5] for concurrent flame spread and Di Blasi [6] for opposed flame spread, solid fuel is treated as consisting of two components: combustible pyrolysate and non-combustible char. Char formed from pyrolysis of virgin fuel is considered to occupy the initial volume of the virgin fuel. The study in [5] focused on model development for thin charring fuel under concurrent flow conditions and showed a good match of prediction with the experiment. The work in [6] is focused on the influence of

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Nomenclature

$\bar{A}_s$	Virgin fuel pre-exponential factor ($= 9.8 \times 10^{6}$ mm/s)
A_s	Non-dimensional virgin fuel pre-exponential factor ($= \bar{A}_s/\bar{U}_R$)
$\bar{A}_{char}$	Char oxidation pre-exponential factor ($= 10^{6.8}$ s $^{-1}$)
A_{char}	Non-dimensional char oxidation pre-exponential factor ($= \bar{A}_c/(\bar{U}_R/\bar{L}_R)$)
A_{CS}	Non-dimensional cross-sectional area of the fuel (πr_f^2)
A_{surf}	Non-dimensional surface area per unit length of the fuel ($2\pi r_f$)
B_O	Boltzmann number ($= \rho^* c_p^* \bar{U}_R / (\sigma\ \bar{T}_\infty^3)$)
$\bar{B}_g$	Gas-phase pre-exponential factor ($= 1.5 \times 10^{12}$ mm^3/ (kg-s))
c_p	Non-dimensional gas- phase specific heat ($= \bar{c}_p / c_p^*$)
$\bar{c}_p$	Gas- phase specific heat $= \sum_{i=1}^{N} \bar{c}_{p,i} Y_i$
c_p^*	Reference gas- phase specific heat ($= 1.38^{3}$ kJ/kgK)
$\bar{c}_{s,v}$	Specific heat of virgin fuel ($\bar{c}_{s,v} = (0.004\overline{T_s} + 0.02)\ kJ/kgK$)
$\bar{c}_{char}$	Specific heat of char/ash ($= 1.46$ kJ/kgK)
$\bar{c}_s$	Solid- phase specific heat ($= \bar{c}_{s,v} * (\rho_s/\rho_{TO}) + \bar{c}_{char} * (\rho_c + \rho_{ash})/\rho_{TO}$)
c_s	Non-dimensional specific heat of solid ($= \bar{c}_s / c_p^*$)
Da	Damköhler number ($= \alpha^* \rho^* \bar{B}_g / \bar{U}_R^2$)
D_i	Non-dimensional diffusion coefficient of species i ($\rho D_i / \rho^* D_i^*) = (T/T^*)^{0.7}$ (Sutherland law)
$\bar{E}_g$	Gas- phase activation energy ($= 1.25 \times 10^5$ kJ/kmol)
E_g	Non-dimensional gas- phase activation energy ($= \bar{E}_g/(\bar{R}_u\ \bar{T}_\infty)$)
$\bar{E}_s$	Solid -phase activation energy ($= 10.9 \times 10^4$ kJ/kmol)
E_s	Non-dimensional solid phase activation energy ($= \bar{E}_s/(\bar{R}_u\ \bar{T}_\infty)$)
$\bar{E}_{char}$	Char oxidation activation energy ($= 1.16 \times 10^5$ kJ/kmol)
E_{char}	Non-dimensional char oxidation activation energy ($= \bar{E}_{char}/(\bar{R}_u\ \bar{T}_\infty)$)
f_i	Stoichiometric mass ratio of species i / fuel in gas phase
F_i	Stoichiometric ratio of species i/char in char oxidation reaction
$\bar{g}$	Gravitational acceleration
$\bar{g}_e$	Gravitational acceleration on the surface of earth ($\bar{g}_e = 9.81$ m/s^2)
g	Non-dimensional gravitational acceleration ($\bar{g}/\bar{g}_e$)
G	Total incident radiation
h_i	Non-dimensional enthalpy of species i $= (\bar{h}_i^o + \int_{\bar{T}_o=298\ K}^{\bar{T}} \bar{c}_{p,i} d\bar{T}) / c_p^* \bar{T}_\infty$
$\Delta\bar{H}_R^o$	Heat of combustion ($= 16.9 \times 10^3$ kJ/kg)
ΔH_R^o	Non-dimensional heat of combustion ($= \Delta\bar{H}_R^o/(c_p^* \bar{T}_\infty) = 40.9$)
I	Intensity of gas radiation
I_b	Blackbody intensity at local temperature
k	Non-dimensional gas thermal conductivity ($= \bar{k} / k^*$)
k^*	Reference gas thermal conductivity ($= 4.6 \times 10^{-6}$ kJ/(m-s-K))
$\bar{k}_s$	Thermal conductivity of solid fuel ($= 1.73 \times 10^{-5}$ kJ/(m-s-K))
k_s	Non-dimensional solid thermal conductivity ($= \bar{k}_s/k^*$)
K	Absorption coefficient of the medium
L	Non-dimensional latent heat of pyrolysis ($= 0$)
Le_i	Lewis number of species i ($Le_F = 1, Le_{O2} = 1.11, Le_{CO2} = 1.39,\ Le_{H2O} = 0.83,$)
$\bar{L}_R$	Reference length (gas-phase thermal length, $(\alpha^*/\bar{U}_R)$)
$\overline{\dot{m}}''_s$	Mass flux from solid ($= \bar{A}_s \bar{\rho}_s \exp(-E_s/T_s)$)
$\dot{m}''_s$	Non-dimensional mass flux from solid ($= \overline{\dot{m}}''_s / (\rho^* \bar{U}_R)$)
$\dot{m}'''_c$	Non-dimensional mass of carbon consumed per unit volume ($= \overline{\dot{m}}'''_c / (\rho^* \bar{U}_R/\bar{L}_R)$)
$\dot{m}'''_o$	Non-dimensional mass of oxygen consumed per unit volume ($= \overline{\dot{m}}'''_o / (\rho^* \bar{U}_R/\bar{L}_R)$)
p	Non-dimensional pressure ($= (\bar{p} - \bar{p}_\infty)/(\rho^* \bar{U}_R^2)$)
$\bar{p}_\infty$	Ambient pressure ($= 1$ atm)
$\bar{q}_r$	Gas radiation heat flux
q_c''	Non-dimensional conduction heat flux from gas to fuel surface ($= \overline{q_c}''/c_p^* \rho^* \bar{U}_R$)
q_r''	Net radiation heat flux at the fuel surface ($= \bar{q}_r''/\sigma \bar{T}_\infty^4$)
$\bar{q}_{char}$	Heat release due to char oxidation per unit mass ($= 28 \times 10^3$ kJ/kg)
q_{char}	Heat release due to char oxidation per unit mass ($= \bar{q}_{char}/(c_p^* \bar{T}_\infty)$)
q_r^{r+}, q_r^{r-}	Positive and negative component of q_r in r-direction
q_r^{x+}, q_r^{x-}	Positive and negative component of q_r in x-direction
r	Non-dimensional r-coordinate ($\bar{r}/\bar{L}_R$)
$\bar{r}_f$	Radius of the fuel ($= 0.4$ mm)
r_f	Non-dimensional radius of the fuel ($= \bar{r}_f / \bar{L}_R$)
$\bar{R}_u$	Universal gas constant ($= 8.305$ kJ/(kmol-K))
Re	Reynolds number ($= \rho^* \bar{U}_R \bar{L}_R / \mu^*$)
R^*	Universal gas constant (8.314 kJ/mol-K)
T^*	Reference temperature (1250 K)
T	Non-dimensional gas-phase temperature ($\bar{T}/T^*$)
T_L	Non-dimensional temperature at which latent heat is given
T_s	Non-dimensional solid-phase temperature ($= \overline{T_s}/\ \bar{T}_\infty$)
$\bar{T}_\infty$	Ambient temperature ($= 300$ K)
t	Non dimensional time ($= \bar{t}/t_R$)
t_R	Reference time ($= \alpha^*/\bar{U}_R^2$)
$\bar{u}$	Velocity in x-direction
u	Non-dimensional velocity in x-direction ($= \bar{u}/\bar{U}_R$)
$\bar{U}_B$	Buoyant reference velocity $[g_R \beta_R (T_\infty - T_F) \alpha^*]^{1/3}$
$\bar{U}_R$	Reference velocity ($=$ max ($\bar{U}_\infty + \bar{U}_B$), 50 mm/s)
$\bar{U}_\infty$	Forced flow velocity
$\bar{v}$	Velocity in r-direction
v	Non-dimensional velocity in r-direction ($= \bar{v}/\bar{U}_R$)
v_w	Non-dimensional velocity in r-direction at the solid surface
$\vec{V}$	Non-dimensional velocity vector ($= u\ \hat{i} + v\ \hat{j}$)
$\Delta\forall$	Non-dimensional elementary volume of pine needle
V_f	Dimensional flame spread rate
v_f	Non-dimensional flame spread rate ($= V_f/\bar{U}_R$)
x	Non-dimensional x-coordinate ($\bar{x}/\bar{L}_R$)
Y_i	Mass fraction of species i (i = F, O_2, CO_2, H_2O)
Y_{pyro}	Mass fraction of pyrolysate ($= 0.62$)
Y_c	Mass fraction of carbon present in char ($= 0.342$)
Y_{ash}	Mass fraction of ash present in char ($= 0.038$)
Y_{char}	Mass fraction of char ($= Y_c + Y_{ash}$)