Case Studies in Thermal Engineering 12 (2018) 301–311

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

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

Influence of thermal contact on heat transfer from glowing firebrands

Alok Warey

General Motors Global Research and Development, 895 Joslyn Avenue, Pontiac, MI 48340, USA

ARTICLE INFO

Keywords:
Wildland-urban interface (WUI) fires
Firebrands
Heat transfer
Thermal contact resistance

ABSTRACT

The influence of thermal contact between a glowing firebrand and the target fuel bed on the resultant heat transfer into the fuel bed was investigated in this study. A zero dimensional (0-D) model for the firebrand coupled to a transient two dimensional (2-D) explicit finite difference model for the fuel bed were used simulate transient heat transfer from a firebrand deposited on a fuel bed. Two firebrand shapes, a disk shaped firebrand in contact with the fuel bed and a cylinder shaped firebrand with a protruding node in contact with fuel bed, were considered. A model was proposed to estimate the thermal contact resistance between the firebrand and the target fuel bed. Heat transfer from a cylinder shaped firebrand with two contact points was also investigated. The model developed in this study provided detailed information on the temperature distribution and thermal penetration depth in the target fuel bed. Predictions made by the model were in qualitative agreement with experimental data reported in the literature. The firebrand thermal contact resistance model presented in this study can be a useful tool to account for variations in firebrand shape and surface irregularities in both the firebrand and the target fuel bed.

1. Introduction

Ignition of surrounding fuel elements by wildland fire generated firebrands or firebrand spotting is a dominant mechanism for the spread of both wildland and wildland-urban-interface (WUI) fires [1]. Firebrands or embers generated by wildland fires are transported over significant distances downwind and can ignite secondary fires far from the fire front [2]. The deposited firebrands heat up the surface of the fuel bed, resulting in the formation of flammable air/fuel mixtures above the fuel bed. Continued heat supplied from the firebrands leads to ignition [3]. A better understanding of how these transported firebrands ignite fuel beds can help mitigate fire spread in communities that are in the wildland-urban-interface.

Ignition of various fuels by firebrands has been extensively studied through experimental measurements by researchers at the National Institute of Standards and Technology (NIST) [1–6]. Experiments were performed for both flaming and glowing firebrand impact. Several shapes and sizes of firebrands such as disks, cylinders and cubes as well as fuel beds of common materials in and around homes/structures were investigated. In general, their data suggests that exposure to flaming firebrands almost always results in ignition, while glowing firebrands may or may not lead to ignition. In addition, flux of firebrands, the size of firebrands and the magnitude of air flow were important parameters in the ignition propensity of a fuel bed. Three types of ignition events were reported: 1) Smoldering ignition, 2) Flaming ignition and 3) Smoldering to Flaming ignition transition. Other experimental studies with metal particles have also been reported [7].

Several models have been developed to calculate trajectories, combustion rates, and lifetimes of metal particles and burning

E-mail address: alok.warey@gm.com.

https://doi.org/10.1016/j.csite.2018.04.018
Received 2 February 2018; Received in revised form 23 April 2018; Accepted 29 April 2018
Available online 03 May 2018

Nomenclature

0-D	Zero dimensional
2-D	Two dimensional
A	Surface area of the firebrand, m^2
A_c	Contact area of the firebrand, m^2
c	Specific heat, J/kgK
CFD	Computational fluid dynamics
D	Diameter of the firebrand, m
$F_{F\rightarrow Fuel\ bed}$	View factor between the firebrand and fuel bed
h	Convective heat transfer coefficient, W/m^2K
h_c	Conductance through the contacting points, W/m^2K
h_g	Conductance through the gas that fills the gaps, W/m^2K
h_j	Thermal contact conductance, W/m^2K
h_r	Radiation conductance, W/m^2K
H_c	Microhardness, kPa
ΔH_c	Heat of combustion, MJ/kg
k	Constant, m^{-1}
k_{air}	Thermal conductivity of air, W/mK
$k_{Firebrand}$	Thermal conductivity of the firebrand, W/mK
$k_{Fuel\ Bed}$	Thermal conductivity of the fuel bed, W/mK
k_s	Harmonic mean of the thermal conductivity, W/mK
m	Firebrand mass, kg
Δm	Change in firebrand mass, kg
m_o	Initial mass of the firebrand, kg
m_s	Mean absolute asperity slope of the interface
NIST	National Institute of Standards and Technology
Nu	Nusselt number
p	Integer
P	Contact pressure, kPa
P_{gas}	Gas pressure, atm
P_o	Reference pressure, atm
Pr	Prandtl number
$q''_{F\rightarrow Fuel\ Bed}$	Radiation heat flux from the firebrand to the fuel bed, W/m^2
q_{cond}	Conduction heat transfer, W
q_{conv}	Convection heat transfer, W
q_{rad}	Radiation heat transfer, W
$\dot{q}_{gen}$	Heat generated, W
$R_{Contact}$	Thermal contact resistance, m^2K/W
Re_D	Reynolds number
RMS	Root Mean Square
$R_{Spreading}$	Thermal spreading resistance, K/W
R_{Total}	Total thermal resistance, K/W
t	Time, s
Δt	Time step, s
T	Temperature in the fuel bed, K
T_{gas}	Gas temperature, K
T_F	Transient firebrand temperature, K
$T_{Fuel\ Bed}$	Mean temperature of the fuel bed, K
T_∞	Ambient temperature, K
T_o	Reference temperature, °C
$T_{Surface}$	Mean surface temperature of the fuel bed, K
U	Wind Speed, m/s
V	Volume of the firebrand, m^3
WUI	Wildland-urban interface
x,y	Coordinates
Δx	Mesh spacing in x-direction, m
Y	Effective gap thickness, m
Δy	Mesh spacing in y-direction, m

Greek Symbols

α	Thermal diffusivity of the fuel bed, m^2/s
ε_F	Emissivity of the firebrand
$\varepsilon_{Fuel\ Bed}$	Emissivity of the fuel bed
ν	Kinematic viscosity of air, m^2/s
θ	Angle between the firebrand and the fuel bed, °
ρ	Density of the firebrand, kg/m^3
σ	Stefan-Boltzmann constant, 5.67×10^{-8} W/m^2K^4
$\sigma_{Firebrand}$	RMS Surface roughness of the firebrand, m
$\sigma_{Fuel\ Bed}$	RMS Surface roughness of the fuel bed, m
σ_s	RMS surface roughness of the contacting asperities, m

embers lofted by the fire plume [8–10]. These models show that burning embers or firebrands can be carried by winds for long distances, due to their low density. Additionally, these embers can land on surrounding fuel beds still burning/glowing. At the same time they may carry less heat than their metal counterparts [9].

A limited set of numerical models have been developed to investigate the interaction of the firebrand with a target fuel bed. Jones [11,12] used the "hot spot" theory to investigate the problem analytically. Zvyagils'kaya and Subbotin [13] and Grishin et al. [14] applied numerical models that considered a porous condensed-phase fuel bed that represented natural vegetation.

Lautenberger et al. [15] developed a 2-D numerical model for the potential ignition of a powdered cellulose bed by an ember or hot metal particle. The model consisted of a computational fluid dynamics (CFD) representation of the gas-phase coupled to a heat transfer and pyrolysis model for the porous fuel bed. In their study the ember was treated as a volumetric heat source. The model provided qualitative information regarding the mechanisms that lead to ignition in a porous fuel bed that agreed qualitatively with experimental observations. Yin et al. [16] used a bulk energy balance approach to develop a correlation between the ignition time and moisture content of pine needles attacked by firebrands.

In this study, transient heat transfer resulting from the interaction of the firebrand with the target fuel bed was modelled using a coupled 0-D model for the firebrand and a transient 2-D explicit finite difference model for the fuel bed. This approach allowed for simultaneous examination of both the temperature evolution of the firebrand and the resultant effect on heat transfer into the target fuel bed. The model provided detailed information on the temperature distribution and thermal penetration depth in the target fuel bed. A model was proposed to estimate the thermal contact resistance between the firebrand and the target fuel bed. The model was used to calculate the thermal contact resistance between two conforming rough surfaces for a disk shaped firebrand. A more likely scenario of poor contact with the target fuel bed was investigated by considering a cylinder shaped firebrand with a protruding node in contact with fuel bed. The research study provides a framework to simulate surface irregularities of the firebrand and the resultant