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# Stochastic modeling of firebrand shower scenarios

Ali Tohidi[a,*], Nigel B. Kaye[b]

[a] Department of Fire Protection Engineering, University of Maryland at College Park, J.M. Patterson Building, College Park, MD 20740, USA
[b] Department of Civil Engineering, Clemson University, Glenn Department of Civil Eng. South Palmetto Blvd, Clemson, SC 29634, USA

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## ABSTRACT

Firebrand shower and its subsequent spot fires are responsible for more than half of the ignitions reported during wildfires, in particular at wildland urban interface (WUI) areas. The firebrand transport is a highly stochastic and nonlinear problem which directly influences the spotting distribution. Hence, a coupled stochastic model of firebrand showers, that is thoroughly and systematically validated against large scale wind tunnel experiments of lofting and downwind transport of model firebrands, is presented. It is shown that the developed model predicts the first and second order statistics of the flight accurately in relation to the experimental data. The sensitivity of the model to the initial conditions of the flight as well as the velocity field characteristics are examined.

## 1. Introduction

Detrimental consequences of Climate Change such as rise in temperature, more severe and frequent droughts, and changes in precipitation patterns, as well as soil moisture index, have made wildfires a more extreme and ubiquitous phenomenon throughout the globe [1]. Each year, on average, wildfires burn millions of acres of land not only in the United States [2] but also in other parts of the world such as Iran where, more than 6% of the forests are being destroyed by them [3]. Regardless of the ecological and social impacts of wildfires, they expose people, properties, and infrastructure to a great threat. Unfortunately, recent land development trends at the wild-land urban interface (WUI) have drastically increased these risks and their associated costs [1,2,4]. Apart from the economic burden, once a wildfire happens the main responsibility is to contain and protect people, property, and mitigate the effects. To this end, understanding wildfire spread mechanisms is of paramount importance. The three pathways by which wildfires propagate are convective heat transfer (direct flame impingement on the fuel sources), radiant exposure (ignition of fuels/vegetation adjacent to large flames), and firebrand shower [2]. While convective and radiant heat transfer may propagate fire through forests, recent studies suggest that exposure to firebrand showers, particularly in WUI communities, is the main cause of fire spread [1,2,5].

Firebrand shower also known as fire spotting is a convoluted multi-physics phenomenon that consists of three stages; first, firebrand formation and breakage from burning vegetation or wooden elements, second, lofting and downwind transport of these firebrands through the wildfire plume envelope and atmospheric boundary layer, and finally, ignition of spot fires upon landing on fuels [6]. Fig. 1, illustrates a schematic of the firebrand shower phenomenon. A variety of parameters such as the size, shape, number, and mass (flux) of firebrands, as well as the moisture content of the fuel bed, terrain characteristics, meteorology, and exposure time to radiant and convective heat fluxes from firebrands [7] are involved in estimating the susceptibility of a region to spot fires. Among various stages and agents that affect fire spotting, firebrand flight is a highly complex stochastic process that strongly influences the maximum downwind transport of firebrands. Hence, the lofting and downwind transport has been extensively studied compared to other stages, namely firebrand generation and spot fire ignition.

To date, most transport models are extensions of the work of Tachikawa [8,9] on debris flight models, which characterizes the transport based on the mass and shape of particles with a set of nonlinear momentum equations. Due to aerodynamic complexities, transport models, specifically, for compact (spherical) [10,11], plate-like, and rod-like [12,13] particles have been developed. However, application of these models to the firebrand shower problem has not been promising as many simplified assumptions were involved in the model development procedure. For instance, customarily in previous studies [14–17], it is assumed that the relative velocity vector is either always normal to the largest area of firebrands, in order to estimate the maximum flight distance, or is aligned with their principal axis. Consequently, this automatically eliminates/reduces the side lift force, and converts the three-dimensional (3D) trajectory of firebrands to two-dimensional (2D), despite 3D motion being an observed flight

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[*] Corresponding author.

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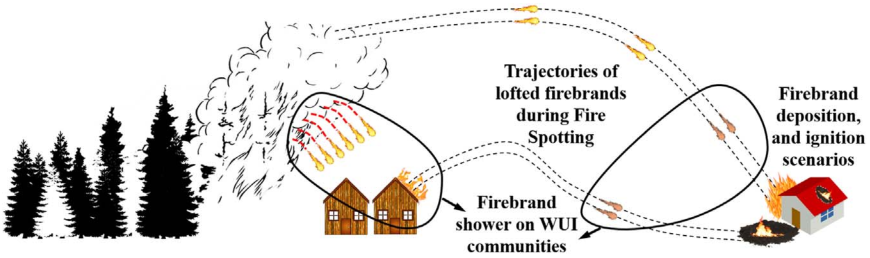

**Fig. 1.** Schematic of the firebrands shower exposure and its role in wildfire spread within WUI communities.

characteristic of these objects [18]. Others [19–21] reduce the order of aerodynamic complexity by assuming compact form for firebrands/debris in their particle transport models, although there is a growing body of experimental and field observations that thin disks and rod-like (cylindrical) forms are the most common shapes of firebrands generated from WUI fires [6,4]. Also, Koo et al. [22] argues that the compact model is the most difficult shape of a given mass to get lofted through the fire plume. Collectively, there has been limited work done on firebrands with non-compact forms [1,23].

On this matter, there exist some studies [6,15,16,24] where either the time-averaged velocity field of a fire plume through the boundary layer cross-flow was used or firebrands (mostly disk-shape) were released from a certain height through a uniform time-averaged boundary layer, i.e. lofting and downwind transport were decoupled. With regard to cylindrical-shape firebrands, the aerodynamic force coefficients were measured by Marte et al. [25], over a limited range of parameter space, and adopted in a six-degree-of-freedom (6-D.O.F.) transport model by Radbill and Redman [26]. For rod-like debris, there is very limited literature [27–29] available which in almost all of them the flight characteristics are measured or modeled solely based on the angle of attack, that is the tilt angle has been ignored. Nonetheless, in a series of influential wind tunnel experiments Richards et al. [13], Richards [30] measured the steady aerodynamic force and moment coefficients of plate-like and rod-like objects in terms of variations in both the angle of attack and the tilt angel. These results were, then, incorporated to a deterministic three-dimensional 6-D.O.F. numerical transport model and, qualitative comparisons between the simulated trajectories and wind tunnel experiments were presented. Later, Richards [31] showed that although the aerodynamic force and moment coefficients might change by either rotation of the projectiles or turbulent characteristics of the velocity field, unsteady force and moment coefficients are only important for early stages of the flight where the accelerations are high. Therefore, plate and rod-like firebrand (debris) transport models that are developed using steady aerodynamic force and moment coefficients [30,32] are likely to account for the complete flight behavior and may deliver accurate results with high confidence levels, namely proper estimation of the first and second order statistics of the trajectories. Indeed, this is crucial as the downwind travel distance, i.e. ground distribution of firebrands or potential spotting distribution [33], is a very important measure in assessing the likelihood of spot fire occurrence in a fire prone area. Hence, given that the firebrand transport is naturally a highly stochastic and nonlinear phenomenon and reliability of the estimated risks as well as the decision making costs associated with firebrand showers are dependent on properties of the spotting distribution [1,33], adopting a probabilistic approach is necessary. This is achieved, here, by adopting the deterministic transport model of Richards [30] and implementing it to a stochastic modeling approach. In fact, prior to this process, the transport model has been experimentally validated through Metropolis Monte-Carlo simulations of the free-fall experiments conducted; see Tohidi [23]. Details of the free-fall experiments as well as the validation process, where it is shown that the transport model is capable of predicting the first and second order statistics of the firebrands' (debris) flight such that the simulation results are not statistically significantly different from the free-fall experiments [23], are not within the scope of this study.

Regarding stochastic modeling, although physics-based probabilistic models [33–35] are available, similar to almost all of the previous works on fire spotting, they suffer from either decoupling lofting from downwind transport or lack of thorough experimental validation. In fact, except very few studies [17] with limited parameter space, there was no experimental data set for evaluating the performance of existing firebrand (debris) transport models through firebrand shower scenarios, even for Richards [30] model. However, the lack of experimental data gap is covered by conducting the most comprehensive set of lofting and downwind transport of non-combusting rod-like model firebrands, with different aspect ratios, through large scale wind tunnel experiments; see [1, chapter 5]. Given the availability of experimental data and a deterministic transport model, which is capable of modeling flight characteristics provided that a sufficient subset of the ensemble of transport is simulated, the main objective of the present study is to develop a coupled stochastic parametric model for firebrand transport and, systematically evaluate its performance using wind tunnel data of Tohidi and Kaye [1]. In this regard, the Monte-Carlo type simulation results of this model, which couples the Large Eddy Simulation (LES) resolved velocity field induced by the interaction of the fire plume and atmospheric boundary layer with a 3D deterministic 6-D.O.F. firebrand flight model [30], are presented. The experimentally validated stochastic model not only provides better understanding of the firebrand flight but also paves the way towards development of advanced classifiers which eventually lead to a more reliable fire spotting risk estimation. Moreover, the discussed methodology and findings here, as well as the experimental data on model firebrands' flight by Tohidi and Kaye [1], may be invaluable for modeling debris/particle transport within other extreme events such as hurricanes, storms, and tornadoes. The remaining parts of this study are organized in the following way. In the next Section 2 the model development and methodology as well as the wind tunnel experiments of Tohidi and Kaye [1] are described. The results and discussions are then presented followed by concluding remarks.

## 2. Model development

This section describes the development procedure of a coupled stochastic parametric model of firebrand transport. However, it is necessary to present a brief overview of the large scale wind tunnel experiments of the firebrand shower scenarios, as their data is employed to validate the model.

### 2.1. *Wind tunnel experiments*

Boundary layer wind tunnel experiments of fire spotting were run using non-combusting polyurethane model firebrands with density $\varrho = 30\ \mathrm{kg/m^3}$, side aspect ratio $\eta_s = L_x/L_y = 1$, and different longitudinal aspect ratios of, i.e. $\eta = L_z/L_{x,y} = 1$, 4 and 6, as shown in Fig. 2-(a). The dimension of all sides in the $\eta = 1$ model firebrands were $L_x = L_y = L_z = 1\ \mathrm{cm}$ and for other aspect ratios $L_x = L_y = 0.5\ \mathrm{cm}$. The tests were conducted in Clemson University's wind tunnel testing

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