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Aerodynamic characterization of rod-like debris with application to firebrand transport

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ABSTRACT

Aerodynamics of the firebrands' flight is fundamental to fire spotting; yet, this phenomenon is relatively poorly understood. Variants of Tachikawa's transport models have been developed for different shapes of debris but, only simplified versions are implemented in firebrand transport models. Failure to include lift and rotational forces reduces the problem to a two-dimensional one, in contrast to the 3D trajectories observed. As such, many studies may have under-/overestimated the flight distance and failed to capture the spotting distribution, accurately. Also, there is virtually no detailed quantitative experimental validation available for rod-like debris transport models. Hence, a set of free-fall experiments with non-combusting model firebrands were run in the absence of cross-wind. The results are employed for verification and performance evaluation of a 3D deterministic 6-Degrees-Of-Freedom (DOF) rod-like debris transport model. It is shown that a transport model must include the complete 6-DOF aerodynamics of the debris for estimating the flight characteristics, such that results are not statistically significantly different from the experimental data. The findings have applications beyond firebrand transport, as they represent the most comprehensive experimental data set and analysis of rod-like debris transport, currently in the literature.

1. Introduction

Wildfires expose people, properties, and ecosystems to a pervasive threat. Each year, they burn more than 800 million acres of land throughout the globe of which the United States' share is approximately 7–9 million acres (Howard, 2014). As Climate Change leads to a rise in temperature, more severe and frequent droughts, and changes in precipitation patterns, the risk of wildfires increases dramatically. Also, land development trends at the wild-land urban interface (WUI) have increased the number of at-risk properties and infrastructures even further. For instance, housing construction in WUI areas has resulted in an increase of at-risk homes from 37 to 47 million in the U.S., according to Foster (2014). As a result wildfires are becoming costlier than current estimates, which in the U.S. is between $20 to $125 billion annually (Howard, 2014).

Apart from the economic burden on the federal government, once a wildfire starts the main responsibility is to contain the fire and protect people, properties, and infrastructure. To this end, understanding wildfire spread mechanisms is of paramount importance. Although wildfires can propagate through convective heat transfer and radiation, there is a growing body of evidence to suggest that firebrand showers and their subsequent fire spotting (Tohidi and Kaye, 2017b) are the source of heat transfer (Caton et al., 2016) that leads to sporadic (stochastic) ignition of fuel beds, in particular houses in WUI areas. In fact, while flame impingement of fuel beds (convective heat transfer) and radiation can cause fire spread in forests, firebrand spotting is one of the major causes of fire spread in WUI areas (Manzello et al., 2007a; Tohidi and Kaye, 2017a).

Firebrand showers and their subsequent fire spotting are complex multi-physics phenomena that involve firebrand formation (Tohidi et al., 2017), lofting through the envelope of buoyant plumes and thermals formed above the flame zone (Tohidi and Kaye, 2016), various lofting to downwind transport transition scenarios (Tohidi and Kaye, 2013), flight through the atmospheric boundary layer (Albini, 1983; Tohidi and Kaye, 2017b), and spot fire ignition upon landing. Many factors such as size, shape, number, and mass of firebrands, moisture content of the fuel bed, terrain, meteorology and the time of exposure to radiant and convective heat fluxes (Boonmee and Quintiere, 2002) are involved in estimating the susceptibility of a region to spot fires. However, among various stages and agents that affect fire spotting, firebrands' transport is a highly

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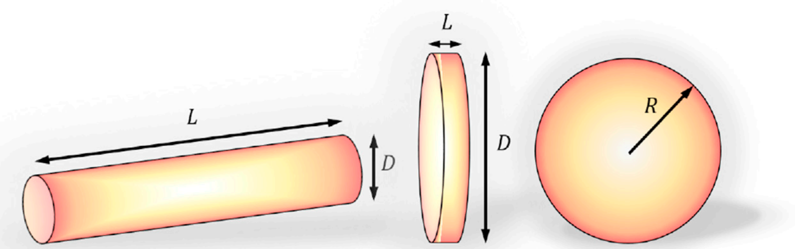

Fig. 1. Shown is the schematic of firebrands (debris) in different shapes, i.e. cylinder (far-left), disk (middle), and sphere (far-right), with their corresponding geometric parameters. For a given mass, the radius of sphere in terms of diameter and aspect ratio η (geometric characteristics of other shapes) can be written as $R = \left(\frac{3}{16}\eta D^3\right)^{1/3}$.

complex stochastic process that strongly influences the maximum downwind transport of firebrands and subsequently spotting distribution. The spatial distribution of landed firebrands, namely the spotting distribution, is a very important measure in assessing the likelihood of a spot fire for a region. Also, the statistics of this parameter depends on the velocity field, induced by the interaction of the boundary layer and the fire plume, and turbulence characteristics of the velocity field (Momen and Bou-Zeid, 2017) as well as the physical and chemical properties of firebrands (Baroudi et al., 2017).

To date, most of the transport models are based on the windborne debris flight models of Tachikawa (2012, 1988) which are written in terms of debris mass and shape. Various models have been developed for compact (Baker, 2007; Holmes, 2004), rod-like, and plate-like debris (Richards et al., 2008). However, only simplified versions of these models have been applied to firebrand flight. For instance Anthenien et al. (2006), Kortas et al. (2009), Wadhwani et al. (2017), and Koo et al. (2012). assume that the relative velocity vector is always normal to the largest area of the firebrand to get the maximum flight distance. This automatically eliminates side lift force and converts the three-dimensional (3D) trajectory of firebrands to two-dimensional (2D), despite the fact that the 3D motion is an observed characteristic of such objects (Visscher and Kopp, 2007). Following the same trend, Kortas et al. (2009). presents the experimental validation of a numerical model for transport and combustion of cylindrical and disk-shape firebrands in which trajectories are assumed to be 2D and rotation of firebrands is neglected, since the incidence angle is prescribed beforehand.

On the same note, Bhutia et al. (2010). considers a compact (spherical) shape for firebrands to numerically investigate the differences in trajectories of firebrands being transported through a classical two-dimensional plume model with a coupled fire/atmosphere Large Eddy Simulator. Similar to Bhutia et al. (2010), Kortas et al. (2009), and Koo et al. (2012), recently, Wadhwani et al. (2017) have conducted a series of experiments for validating the existing Lagrangian particle transport model of Fire Dynamic Simulator (FDS) (McGrattan et al., 2000) in simulating short-range transport of uniform non-combusting cubiform and cylindrical model firebrands. The spotting distribution of cubiform model firebrands obtained from simulations, using the Lagrangian transport model of FDS, is reported to corroborate with experimental results; however, this was not the case for cylindrical model firebrands as the order of aerodynamic complexity is much higher than the cubiforms and customary simplifying assumptions do not lead to capturing the underlying physics with reliable accuracy. In general, considering compact form for firebrands is an overly simplified model as they are predominantly in cylindrical or disk shape (Tohidi et al., 2015). Also, compact firebrands are the most difficult shape to get lofted for a given mass (Koo et al., 2012). This can be shown using the ratio of drag force on a sphere to other shapes, i.e. cylinder and disk, if one assumes an identical velocity field for firebrands of various shapes but the same density. The drag ratio, ζ, can be written in terms of the aspect ratio of firebrands, namely $\eta = L/D$ where L is the length/thickness and D is the diameter as shown in Fig. 1.

For a turbulent flow, ζ can be approximated as

$$\zeta = \frac{F_{d,\ Sphere}}{F_{d,\ Cylinder/Disk}} \approx \begin{cases} 0.7\eta^{-1/3}, & \eta \geq 1 \\ 0.5\eta^{2/3}, & \eta < 1 \end{cases}. \tag{1}$$

According to equation (1), for all possible values of η, that is $\eta \geq 1$ (cylinders) and $\eta < 1$ (disks), the drag ratio is less than one which implies that, for a given mass the aerodynamic force per unit weight in compact firebrands is less than the corresponding cylindrical and disk-shape firebrands provided that the velocity field is identical. Nevertheless, many studies (Fernandez-Pello, 1982; Holmes, 2004; Lee and Hellman, 1969, 1970; Tarifa et al., 1967; Tarifa et al., 1965; Wadhwani et al., 2017) have utilized the sphere model while few works (Himoto and Tanaka, 2005; Koo et al., 2010; Sardoy et al., 2007, 2008) can be found on disk-shape approximations. However, almost all previous works lack thorough experimental validation.

Despite the overwhelming evidence (both experimental and field) that thin disks and particularly long cylinders are very well representative of firebrands generated during WUI fires (Koo et al., 2012; Manzello et al., 2008), there has been little work done on the flight of these types. Previously, the aerodynamic force coefficients of cylindrical objects are measured by Marte et al. (1976) and the results are used in a six-degree-of-freedom (6-DOF) trajectory model of Radbill and Redman (1976) Similarly, trajectories, velocities and aerodynamic force coefficients of rectangular cylinders are measured by Tachikawa and Harra (1982). Also, Lin (2005) and Lin et al. (2007). reported the planar trajectories of rod-like debris that were released in a wind field parallel to their symmetry plane. However, in most of these studies, the aerodynamic force coefficients and the position of the center of pressure are only functions of the angle of attack, and the center of pressure is always located on the symmetry plane. However, the real situation is more complex than this.

In this regard, the steady aerodynamic force and moment coefficients of plate and rod-like objects were measured in a set of wind tunnel experiments by Richards et al. (2008). which clearly shows that the coefficients are functions of both angle of attack and tilt angle. Further, Richards et al. (2008) incorporate these coefficients into a 6-DOF numerical transport model, and presents some qualitative comparison of the numerical results with the corresponding free flight experiments in a wind tunnel. It is shown, qualitatively, that their model can account for the trajectories of plates with different length and aspect ratios, and long rectangular (rod-like) objects with various side aspect ratios. Moreover, since the angular increment used in Richards et al. (2008)'s measurements were coarse, wind tunnel experiments with finer angular increment were conducted by Richards (2010). In another study by Richards (2012), it is shown that, although 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 the early stages of the flight where accelerations are high.

Given the simplifying assumptions in existing firebrand flight models,