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Comprehensive wind tunnel experiments of lofting and downwind transport of non-combusting rod-like model firebrands during firebrand shower scenarios

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ABSTRACT

To date, due to difficulties in making measurements during wildfires, much of what is known about firebrand showers and the subsequent fire spotting comes from mathematical modeling of the lofting and downwind transport of firebrands. However, these models lack experimental validation. Hence, the coupled lofting and downwind transport of non-combusting rod-like firebrands is experimentally modeled by releasing them through the velocity field of a large scale boundary layer wind tunnel. Complete trajectories of model firebrands are resolved using image processing algorithms. The results show a strong positive correlation between the maximum rise height (z_{max}) and the landing location (x_l) of model firebrands. In addition, it is shown that, given the velocity field, the empirical probability density functions (PDF) of x_l/z_{max} are similar regardless of the firebrands' aspect ratio. This implies that the lofting and downwind transport processes cannot be decoupled in transport models. Analysis of the data reveals that, the larger the aspect ratio of firebrands, the more sensitive their landing locations are to the variability in the velocity field through which they are released. The data set presented herein serves as the most comprehensive experimental evidence for not only firebrand transport studies but also for validating mathematical models for the flight of rod-like debris/brands within the velocity field of other extreme events such as hurricanes.

1. Introduction

Firebrand showers, that may lead to spot fire ignition, are not only a perilous and inevitable phenomenon during wildfires but also in urban fires or any large conflagration. There is a growing body of evidence to suggest that firebrand showers are responsible for fire spread [32]. Observations range from the great fire of London (1666) [12], post-earthquake conflagrations of San Francisco (1906) and Tokyo (1923) [25], recent wildfires in Australia and Greece [35], to numerous other cases; see Koo et al. [25], and Tohidi et al. [49]. Spot fires generated by firebrand showers are highly stochastic and, as the intensity and size of fires grow, they become more severe [4]. This necessitates understanding of firebrand flight mechanisms leading to firebrand showers, as they pose a major threat to people, properties, and infrastructure, particularly at wildland urban interfaces (WUI) [47].

A typical firebrand shower process is as follows. Once a wildfire or any large conflagration occurs, combustion processes such as pyrolysis and char affect the vegetative structures or woody elements. Due to the subsequent thermo-mechanical processes firebrands form and break-off from the burning vegetation/structures [11,49]. Then, firebrands can get lofted up through the fire plume where, if the rise height is sufficient, transition from lofting to downwind transport within the atmospheric boundary layer occurs. For more information on various lofting to downwind transition criteria see Tohidi and Kaye [50]. Critical environmental factors such as topography, direction of the fire line spread, separation due to wind on the lee side of the ridge, and fuel breaks may enhance the air entrainment into the fire plume, increases the updraft and consequently intensify the firebrand shower [18,24]. Ultimately, a spot fire may ignite upon landing on susceptible fuel beds far ahead of the fire front.

The lofting and downwind transport of firebrands through the velocity field generated by the interaction of the fire plume and the atmospheric boundary layer plays a significant role in the fire spotting phenomenon and subsequently wildfire spread. To date many studies have been done on the flight of debris/firebrands through different velocity fields. For instance, in a series of studies Tarifa et al. [45,44] investigated combustion and transport properties of firebrands along

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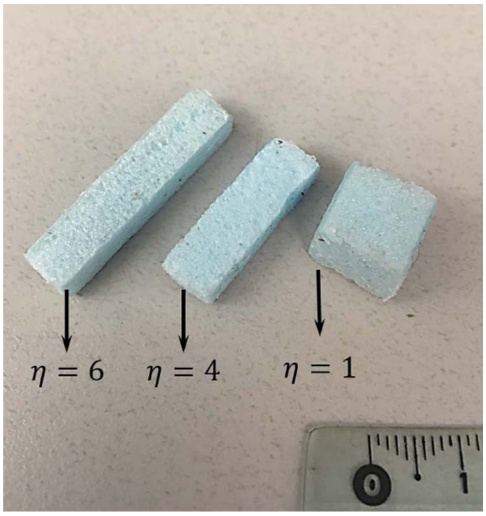

Fig. 1. Polyurethane made model firebrands with different aspect ratios; The scale shows 1 cm in the image space.

with the influence of their size, shape, density, and moisture content on transport in a small scale wind tunnel. These studies were conducted for a very simplified model of firebrands with no rotational effects. The aerodynamic behavior and trajectories of spherical model firebrands through a naturally convective turbulent swirling plume was discussed by Lee and Hellman [27,28]. In addition, Tse and Fernandez-Pello [52], Himoto and Tanaka [20], Anthenien et al. [10], Sardoy et al. [41,39], and Bhutia et al. [13] have modeled fate and transport of different types of firebrands, numerically. Himoto and Tanaka [21] developed and validated an urban fire spread model that, instead of modeling firebrand lofting and transport, uses a probabilistic approach for estimating the firebrand travel distance.

While these studies are of great value in improving our understanding of the processes involved in firebrand transport, a large number of the developed mathematical models are based on simplifying assumptions that raise concerns about their applicability to real fire events. Further, there has been little experimental work [29,38,37] done on the rod-like firebrand/debris transport, and majority of the numerical models suffer from lack of thorough experimental validation. The previous works on (rod-like) debris [52,41,2–9,20,21,45,44,36] have focused on horizontal wind fields and have not examined the interactions of vertical lofting flow with the horizontal atmospheric boundary layer winds. The main objective of this study is to fill this gap by presenting results of an extensive set of large scale wind tunnel experiments for lofting and transport of non-combusting rod-like model firebrands through the scaled-down velocity field of small to medium wildfires.

The experimental results will enable rigorous validation of current and future firebrand flight models. Also, the results have applications beyond firebrand transport, as they provide a broad experimental analysis for transport of rod-like debris with different aspect ratios in a turbulent boundary layer. The remainder of this paper is structured as follows: the experimental setup is discussed in Section 2. In Section 3 the data acquisition technique is presented followed by Section 4 through which the experimental results and analysis are presented. Concluding remarks are drawn in Section 5.

2. Experimental setup

A set of lofting and transport experiments were conducted to examine the flight characteristics of rod-like firebrands lofted vertically into model wildfire velocity field generated by the interaction of the fire plume and the atmospheric boundary layer.

2.1. Brief discussion on scaling

In fluid dynamics, measurements are often performed on models, under controlled conditions, that either share the same characteristics with the actual system or have similitudes with the phenomenon. The concept of similarity permits extension of information in experimental models to the actual phenomena or systems. The essential requirement for complete similarity is that the geometric, kinematic, and dynamic similarity between the model and the phenomenon must be satisfied. However, this is not feasible when one is modeling lofting and transport of firebrands through the velocity field of wildfires. In fact, since very little is known about firebrands generated through a real wildfire, and laboratory studies exhibit a very wide range of sizes and shapes [31–34], the geometric similarity would require an unfeasible amount of experiments. Dynamic similarity is, also, not possible in wind tunnels as pool fires need to be created and then the wind speed scaled to match both the Froude number and plume to wind velocity ratio [51]. For small-scale laboratory fires, even in the largest available

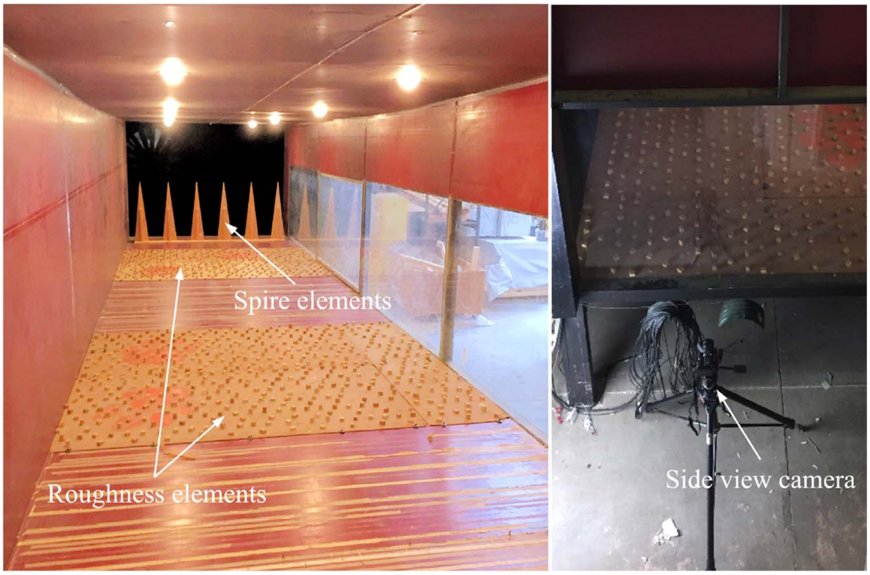

Fig. 2. (Left) Inside the wind tunnel chamber where the surface roughness elements and spire elements are installed. Also, on the right, the camera position at the side view of the release point (jet location) is shown.