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

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the velocity field of other extreme events such as hurricanes.

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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

26 intensify the firebrand shower [18, 24]. Ultimately, a spot fire may ignite upon
27 landing on susceptible fuel beds far ahead of the fire front.

28

29 The lofting and downwind transport of firebrands through the velocity field
30 generated by the interaction of the fire plume and the atmospheric boundary
31 layer plays a significant role in the fire spotting phenomenon and subsequently
32 wildfire spread. To date many studies have been done on the flight of debris/fire-
33 brands through different velocity fields. For instance, in a series of studies Tar-
34 ifa et al. [45, 44] investigated combustion and transport properties of firebrands
35 along with the influence of their size, shape, density, and moisture content on
36 transport in a small scale wind tunnel. These studies were conducted for a
37 very simplified model of firebrands with no rotational effects. The aerodynamic
38 behavior and trajectories of spherical model firebrands through a naturally con-
39 vective turbulent swirling plume was discussed by Lee and Hellman [27, 28].
40 In addition, Tse and Fernandez-Pello [52], Himoto and Tanaka [20], Anthenien
41 et al. [10], Sardoy et al. [41, 39], and Bhutia et al. [13] have modeled fate and
42 transport of different types of firebrands, numerically. Himoto and Tanaka [21]
43 developed and validated an urban fire spread model that, instead of modeling
44 firebrand lofting and transport, uses a probabilistic approach for estimating the
45 firebrand travel distance.

46

47 While these studies are of great value in improving our understanding of the
48 processes involved in firebrand transport, a large number of the developed math-
49 ematical models are based on simplifying assumptions that raise concerns about
50 their applicability to real fire events. Further, there has been little experimental
51 work [29, 38, 37] done on the rod-like firebrand/debris transport, and majority of
52 the numerical models suffer from lack of thorough experimental validation. The
53 previous works on (rod-like) debris [52, 41, 4, 8, 2, 3, 5, 6, 9, 7, 20, 21, 45, 44, 36]
54 have focused on horizontal wind fields and have not examined the interactions
55 of vertical lofting flow with the horizontal atmospheric boundary layer winds.
56 The main objective of this study is to fill this gap by presenting results of an

57 extensive set of large scale wind tunnel experiments for lofting and transport
58 of non-combusting rod-like model firebrands through the scaled-down velocity
59 field of small to medium wildfires.

60

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

69 **2. Experimental setup**

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

74 *2.1. Brief discussion on scaling*

75 In fluid dynamics, measurements are often performed on models, under con-
76 trolled conditions, that either share the same characteristics with the actual
77 system or have similitudes with the phenomenon. The concept of similarity
78 permits extension of information in experimental models to the actual phenom-
79 ena or systems. The essential requirement for complete similarity is that the
80 geometric, kinematic, and dynamic similarity between the model and the phe-
81 nomenon must be satisfied. However, this is not feasible when one is modeling
82 lofting and transport of firebrands through the velocity field of wildfires. In fact,
83 since very little is known about firebrands generated through a real wildfire, and
84 laboratory studies exhibit a very wide range of sizes and shapes [33, 32, 31, 34],

85 the geometric similarity would require an unfeasible amount of experiments.
86 Dynamic similarity is, also, not possible in wind tunnels as pool fires need to be
87 created and then the wind speed scaled to match both the Froude number and
88 plume to wind velocity ratio [51]. For small-scale laboratory fires, even in the
89 largest available wind tunnels, this would lead to very low wind speeds which
90 would lead to a boundary layer that is not in the fully developed turbulent
91 regime.

92
93 Therefore, it is not possible to run wind tunnel experiments of firebrand
94 lofting and transport in which geometric and dynamic similarity are satisfied.
95 Instead, a series of wind tunnel tests were run in which model firebrands were
96 lofted into the wind tunnel boundary layer using a vertical air jet. The stream
97 wise firebrand trajectory was then measured. While the use of a vertical non-
98 buoyant air jet is not directly analogous to a vertical buoyant fire plume the
99 two flows are quite similar. They are both round vertical turbulent shear flows
100 that entrain fluid as they rise due to shear with the surrounding environment.
101 The main difference is that the buoyancy of the plume generates additional
102 vertical momentum as it rises whereas a turbulent jet has a constant vertical
103 momentum flux. This means that a jet will bend horizontally at a lower height
104 compared to a turbulent plume with the same source momentum flux but with
105 an additional buoyancy flux. However, the overall structure of the two flows is
106 similar and the effect of buoyancy on the large scale dynamics can be accounted
107 for in re-scaling [51]. The density of the hot air in the plume will make only
108 a very small difference to the flight trajectory of a firebrand as the buoyancy
109 force acting on the firebrand is negligible. Therefore, the use of a vertical air
110 jet rather than a vertical plume will still provide a valuable model validation
111 data set for firebrand transport models. The main goal of experiments is to
112 develop an experimental data set that can be used to validate mathematical
113 models which can then be applied to full scale fires. More discussion of the use
114 of this data set for firebrand transport model validation will be presented in the
115 final section of this paper.

116 2.2. Setup

117 Boundary layer wind tunnel experiments of fire spotting were run using
 118 non-combusting polyurethane model firebrands with average density of $\varrho =$
 119 30 kg/m^3 , side aspect ratio $\eta_s = L_x/L_y = 1$, and different longitudinal aspect
 ratios, i.e. $\eta = L_z/L_{x,y}$, as shown in figure 1. Here, L_z denotes the major

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

120 side and L_x & L_y denote the minor sides. The dimension of all sides in $\eta = 1$
 121 model firebrands are equal, i.e. $L_x = L_y = L_z = 1 \text{ cm}$, and for the other aspect
 122 ratios $L_x = L_y = 0.5 \text{ cm}$. Low density manufactured polyurethane firebrands
 123 were used instead of natural wood sections for two reasons. First, the more
 124 precise dimensions allowed for greater experimental repeatability, and second,
 125 the Polyurethane was light enough to be lofted vertically by the air jet high into
 126 the wind tunnel tests section whereas sample wood dowel rods were unable to
 127 be lofted.

129

130 The tests were conducted in Clemson University's wind tunnel testing facility
 131 which is classified as a low-speed boundary layer wind tunnel, as the maximum
 132 achievable velocity is less than 100 m/s [46]. Hence, flow compressibility effects

are negligible or very small in the experiments. The test section is comprised of a 3.05 m wide by 2.03 m high open boundary layer with 20 m of fetch. The wind flow is generated by two 1.8 m diameter fans which are controlled by adjustable frequency inverters. The flow is passed through a honeycomb grid, a set of screens and a contraction to produce low turbulence intensity uniform inflow. In order for the boundary layer to be turbulent, a combination of a spire board and surface roughness elements were used; see figure 2-left. The spire board

Figure 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.

consists of 6 triangles with 92.2 cm height and 25.4 cm base that were evenly spread across the 3.05 m width of the wind tunnel immediately downwind of the contraction. The surface roughness elements are made from randomly located rectangular prisms of length 3.2 cm and thickness of 1.6 cm that are stuck to boards with glue. The surface roughness boards covered over 11 m of the upstream section to generate a grass (open flat) terrain exposure [14]. For more details on the specifics of the wind tunnel see Liu et al. [30].

147

148 The velocity field of the fire plume was modeled using an air jet installed in
 149 the floor of the wind tunnel; see figure 3. The 15.2 *cm* diameter jet was created
 150 using two 4 *hp* blowers that were fed into a 58.8 *cm* flow straightener. The jet
 centerline exit velocity could be adjusted between 0 – 12 *m/s*.

Figure 3: Details of the mounted air jet underneath the wind tunnel floor. Also, shown are blowers, and the flow straightener.

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152

153 Experiments were run for combinations of three boundary layer reference
 154 velocities and three jet centerline velocities, in order to model the velocity field
 155 induced by the interaction of the fire plume and the boundary layer. The gener-
 156 ated velocity fields are measured using an *Extech* – 407112 heavy duty hot-wire
 157 thermo-anemometer which has $\pm 0.1 \text{ m/s}$ resolution in the range of 0.2 – 20 *m/s*.
 158 As for of the boundary layer, the velocity measurements are conducted at the
 159 centerline of the wind tunnel test section, exactly 25 *cm* upstream of the jet

centerline when the jet was turned off. Similarly, centerline and radial velocity profiles of the jet were measured with no wind. The cross-sectional velocities were measured at 0.138 m from the jet nozzle exit, where the jet cross-section is level with the wind tunnel's floor. This small space is utilized for releasing model firebrands through the domain. Specific parameter combinations tested in the experiments are set out in table 1. Also, it should be mentioned that the ratio of jet centerline velocity to the boundary layer reference velocity, i.e. $(U_{j|r=0}/U_0)$, is of the order of 4 ± 1 for these tests, and corresponds to the available field data for small scale wildfires [13, 51].

Table 1: Specifics of the non-combusting model firebrands' lofting and transport experiments. Here, U_0 denotes the horizontal component of boundary layer wind tunnel velocity at the reference height of $z_0 = 0.04\text{ m}$, the jet centerline velocity is shown by $U_{j|r=0}$, $\eta = L_z/Lx, y$ is the planks (model firebrands) aspect ratio, and D.O.F. stands for the degrees of freedom (nominal number of releases) for each aspect ratio.

$U_0\text{ (m/s)}$	$U_{j r=0}\text{ (m/s)}$	η	D.O.F.
1.79	12	1, 4, 6	200
	8.05	1, 4, 6	200
	9	1, 4, 6	200
2.23	12	1, 4, 6	200
	8.05	1, 4, 6	200
	9	1, 4, 6	200
2.85	12	1, 4, 6	200
	8.05	1, 4, 6	200
	9	1, 4, 6	200

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169

In the boundary layer the reference height is taken to be $z_0 = 0.04\text{ m}$ to fit the power-law profile, namely $U = U_0(z/z_0)^\alpha$. Sixty second time averaged velocity measurements in a vertical profile showing the boundary layer are presented in figure 4 along with their corresponding power-law fit. Sixty second

Figure 4: Vertical profiles of the boundary layer horizontal (stream-wise) velocity component measured in the wind tunnel. Also, U_0 is the horizontal velocity of the corresponding power-law fits with exponent α and the reference height $z_0 = 0.04 \text{ m}$.

174 time averaged vertical velocity measurements along the centerline of the jet nozzle
175 zle and across the jet cross section are shown in figure 5 for three different outlet
176 velocity configurations. It should be noted that associated uncertainties with
177 the velocity measurements are not presented in these graphs, since they are, at
178 most, less than 3.33% and 1.25% for the boundary layer and jet, respectively.

179

As can be seen in figure 5-left, the normalized time-averaged vertical (stream-wise) velocity profile of the jets are similar and approximately collapse onto a single curve. The time-averaged radial variation in vertical velocity, see figure 5-right, is less consistent due to different inlet conditions. The measurements are

Figure 5: Shown on the left are the time averaged vertical velocities of the jet at the centerline $r = 0$ where r is the radial distance from the jet center; And on the right are cross section stream-wise velocities which are measured at $z = 0.138 m$ from the jet nozzle exit.

in good agreement with the classical data for round jets (see Albertson et al. [1]). Therefore, it is possible to use the integral model of round jets to characterize and quantify the source condition parameters. This can be done using the following equation for the stream wise velocity of the jet [26].

$$\langle U_{j|r=0} \rangle = 7M_0^{1/2} z^{-1}, \quad (1)$$

where M_0 is the initial momentum flux at the source, and z is the vertical distance from the jet virtual origin. In wildfires, M_0 corresponds to the buoyancy-driven momentum at the source which is a function of heat release rate of fire or burning rate of the fuel. Based on equation 1, the time-averaged vertical velocity is proportional to the inverse of distance from the virtual origin (z). This is shown by the log-log plots of the experimental measurements in the quiescent ambient, see figure 6.

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The experimental results in figure 6 clearly demonstrate the length of the potential core is much smaller than the typically observed. This is because of the jet structure in which the air flow is generated by the blowers passes through multiple flexible hoses, and then goes through a flow straightener with honey-

Figure 6: Normalized time averaged vertical velocity of the jet at the centerline.

192 comb mesh. Hence, the jet outflow is highly turbulent and the jet potential core
 193 is eroded in only three diameters downstream. This is much smaller than the
 194 $6.2D$ distance downstream typical of the literature [15, 26], where D is the jet
 195 diameter. Also, the predicted variation of the velocity with z in equation 1 is
 196 well-confirmed. In fact, having a fully developed turbulent jet flow being entered
 197 in a turbulent boundary layer cross-flow ensures that the turbulence effects are
 198 factored in and experiments reasonable approximation of real wildfire scenarios.
 199 This is important for mathematical modeling of firebrand shower phenomenon
 200 as Karimpour and Kaye [23] show that turbulence influences flight statistics of
 201 debris.

202

203 Different combinations of the wind tunnel boundary layer and jet velocity
 204 fields were tested that are analogous to the interaction of a fire plume with the
 205 atmospheric boundary layer. To the best of the authors' knowledge, this is the
 206 first time the coupled lofting and transport of firebrands has been experimentally
 207 examined. Different aspect ratios of rod-like polyurethane model firebrands were

released at or near the centerline of the jet exit. Each aspect ratio was released approximately 200 times for each combination of the boundary layer and jet velocity. For each set of 200 releases the initial orientation (Euler's angles [19]) was varied, randomly. This provided a significant number of samples (degrees of freedom) for statistical analysis. The entire process of lofting and downwind transport of individual model firebrands are recorded from the side view using a *GC-PX100 JVC* camera with 1920×1080 resolution at 60 *fps* (see Figure 2-right).

3. Data acquisition method

The lofting and downwind transport of the model firebrands was recorded from the side with a camera set to be perpendicular to the centerline of the wind tunnel. An image processing algorithm was developed and implemented in the MATLAB environment in order to capture full trajectories of firebrands along with the maximum rise height and downwind distance. The data acquisition technique is discussed below.

3.1. Camera calibration

In order to reach a quasi-steady state, the wind tunnel and the jet were run for 2 – 3 minutes, while the camera was being installed on the side view of the test section. Then, for each set and before releasing the model firebrands into the velocity field, a calibration video was taken in which a designated scale was fixed directly over the jet exit into the wind tunnel chamber. The scale was used to calculate the picture ratio of the images and further calibrate (convert) pixels to units of length. Picture ratio is the fraction of known distances between designated black dots on the scale, here in millimeters, to the corresponding number of pixels between them [16]. In addition, optical distortion due to fish-eye effect and any slight camera misalignment was measured for each set of tests utilizing the Omnidirectional Camera Calibration algorithm [42] and found to be less than $\pm 1 \text{ mm}$ for the presented setup. Figure 7 shows a sample

Figure 7: An extracted calibration image magnified on the scale's area in order to present the utilized scale. There are four points on the scale that build a square with sides of 100 mm , and the other two are used to check the calculated picture ratio.

236 image that is extracted from a calibration video. With regard to accuracy of
 237 the imaging technique, one might argue that according to firebrands' transport
 238 [38, 48] is a highly stochastic phenomenon and trajectories are 3D with lateral
 239 spread which might affect the results. On this note, it should be mentioned
 240 that, a small symmetric lateral spread was observed during the post experimen-
 241 tal clean up where the locations of the model firebrands on the wind tunnel
 242 floor was clustered around the centerline of the tunnel directly downwind of the
 243 release location. However, in these set of experiments, since the aerodynamic
 244 force of the wind tunnel boundary layer on the Polyurethane made model fire-
 245 brands is large enough, the observed lateral spread is very small relative to the
 246 maximum rise height and the maximum downwind distance. Also, due to the
 247 symmetry of the experiments, the lateral spread would have negligible impact
 248 on the estimated first order statistics of the results. For future studies, adding
 249 another camera and conducting stereophotogrammetry would resolve this minor
 250 issue.

251 3.2. Data collection

252 After the calibration operation the scene was emptied and videos were recorded
 253 of model embers being lofted and transported. Per set, model firebrands were
 254 released at least 10 s after the camera was turned on. Since the recording was
 255 being done with 60 *fps*, that provided enough frames to construct the back-
 256 ground image. The firebrand models were then released from approximately
 257 the center of the jet with tweezers such that the jet flow field was disturbed
 258 as little as possible. For each release operation the initial angles of each model
 259 firebrand are varied randomly. Each set of the experiments took between 8 – 11
 260 minutes to record the lofting and downwind transport of 200 samples.

261 3.3. Image processing

262 The videos collected were analyzed using an image processing algorithm that
 263 starts with extracting all frames in a video and constructing a background im-
 264 age. The extracted frames are stored as images on an external hard disk due to
 265 the high volume of the generated data. Using MATLAB, images are read and
 266 converted from RGB to double in gray scale space. This provides more accu-
 267 racy and flexibility in image analysis. The background image is constructed by
 268 averaging over light intensities of at least 100 empty images. On figure 8-left a
 269 sample background image is shown versus a normal frame taken from the emp-
 tied scene of the test section.

Figure 8: (Left) Color coded background image, with light intensities, constructed by averaging over at least 100 empty frames. (Right) an original (untouched) frame, empty from model firebrands presence at the test section while the velocity field is flowing.

270

271

272 The background image is subtracted from all frames. This detects the pres-
 273 ence of model firebrands in the domain. Yet, the obtained image is not practi-
 274 cally useful for calculating the firebrands' position inside the frame. This is due
 275 to the general motion of the firebrands during which they are both translating
 276 and rotating. Rotation causes model firebrands to emit various range of light
 277 intensities such that it is hard to identify all of them by just a global thresh-
 278 olding method; see [17]. In order to resolve this issue, background subtracted
 279 frames are convolved with a rotationally symmetric low-pass *Gaussian* filter
 280 with a square height matrix of 45 pixels and standard deviation of $\sigma_g = 5$ as
 281 shown in figure 9. Convolution of the *Gaussian* filter reduces the noise in the
 282 image and prepares it for intensity mapping. A sample of the smoothed image
 283 is shown on figure 10-(top-right).

Figure 9: The utilized rotationally symmetric low-pass *Gaussian* filter that is used for noise reduction. The given height is color coded with the intensity range before noise reduction.

284

285 The intensities obtained are then mapped to the range of $0 - 1$ with high Γ
 286 function (see [16]) value such that a global thresholding method can be applied.
 287 This operation isolates the pixels that the model firebrands occupy in the image;
 288 see figure 10-(bottom-left). Ultimately, in order to calculate the centroid coordi-
 289 nates of the identified model firebrand, the intensity stretched image is morphed

Figure 10: (Top-left) Untouched image from a model firebrand during its flight through the velocity field. (Top-right) Shown is the result of background subtraction and the *Gaussian* filter convolution on the original image. The image with mapped intensity along with the morphologically opened image are shown at the bottom-left and bottom right, respectively. The dot in the middle is a model firebrand with $\eta = 1$ that is identified in frame 1035 of the video, that is 17 s after the release operation has started for this set of experiments.

290 with the cylindrical (in cases with $\eta = 4$ or 6) and square (in cases with $\eta = 1$)
 291 structuring elements. This process is repeated over all extracted images and re-
 292 sults in resolving full 2D trajectories of the model firebrands during lofting and
 293 downwind transport; see figure 10-(bottom-right). Sample trajectories resulting
 294 from applying this algorithm on a sample video are shown in Figure 11.

295

296 Two recurring problems were observed among the obtained trajectories.
 297 First, some of the trajectories do not include the exact landing location. This is
 298 primarily due to the low light intensity near the floor which makes the algorithm
 299 susceptible to miss the objects as they pass through the camera frame. This
 300 issue is resolved by extrapolation of the obtained trajectories to the elevation of
 301 $z = 0$. The extrapolation is conducted by converting the units from millimeter
 302 to meter such that the remaining distance to the ground, i.e. extrapolation
 303 domain, is normalized between 0-1. This reduces the extrapolation error, since

Figure 11: Calculated trajectories of the model firebrands with aspect ratio $\eta = 1$ in an experimental case where the boundary layer reference velocity was $U_0 = 2.23 \text{ m/s}$ (from right to left), and the jet centerline velocity at the exit (point $[0, 0]$) was 8.05 m/s .

the last three points on the trajectory are chosen as the training set for finding the corresponding point (landing location) on the ground. The same method is applied to the upstream part of the trajectory where the model firebrands lift off through the jet.

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Second, some flights resulted in incomplete or partially identified trajectories. This is caused by either the model firebrands leaving the frame of analysis due to high lofting velocity or low intensity of light during the flight. The later issue is resolved by the data storage technique that is used in the algorithm. This method assigns a tag to each detected object and saves that with the position coordinates. In this way if a trajectory is partially recognized (say if the model firebrand is lofted out of the frame) the subsequent parts can be combined together. The former issue is solved by using characteristics of the completed trajectories. As is evident in figure 12, full trajectories have a pattern if one calculates the adjacent difference in the rise height at each point, namely $\Delta y = y_i - y_{i-1}$. If the resulting vector (for each model firebrand trajectory) is drawn against the order by which the location coordinates are recognized (i.e. i), the pattern has three distinct parts. The first part where Δy is decreasing can be associated with the lofting part, the section with effectively zero slope

323 can be attributed to the lofting to downwind transport transition, and finally
 324 as Δy decreases again the landing part has been started. Even the shortest
 325 complete trajectories have more than 10 identified points in their position coor-
 326 dinates vectors. Incomplete and partial trajectories do not follow such patterns
 327 or simply don't have enough points; This has been confirmed through many tri-
 328 als within the algorithm (figure 12-right). Further, trajectories in which more
 329 than 5% of the identified points are off this pattern are assigned as incomplete.
 330 Lastly, if there is no corresponding partial or incomplete path found for trajec-
 tories with a corrupted tag, they are eliminated from calculations.

Figure 12: The identified pattern in complete trajectories by calculating adjacent differencing
 of the rise height (left). On the right shown are samples of the incomplete or partially complete
 trajectories that do not follow the same pattern as the completed ones.

331

332

333 4. Results

334 Tests were run for all 27 combinations of three wind speeds, jet speeds, and
 335 firebrand aspect ratios. Approximately 200 releases were done for each param-
 336 eter combination, though some of the model firebrands are missed during the
 337 image processing procedure. Therefore, the reported DOFs are not equal to

the nominal value of 200 per set. During the tests, significant variability in the firebrand rise height and downwind flight distance were observed. Firebrand trajectories were quite complex at times and the model firebrands rotated considerably during flight. Some firebrand motion in the cross wind direction was also observed although this was not quantified by the camera system. Comprehensive results of the image processing algorithm applied to the experiments along with the statistical analysis of the trajectories' characteristics are presented in this section.

Figure 13: Obtained trajectories from the image processing analysis. Presented data are trajectories of the cubic firebrand models with longitudinal and side aspect ratio of one, i.e. $\eta = \eta_s = 1$. From left to right, the reference velocities of the wind tunnel boundary layer are 1.79, 2.23, and 2.85 (m/s), and from top to bottom, the jet centerline velocities are 8.05, 9.0, and 12 (m/s).

The captured trajectories are presented in figures 13-15. Generally, the re-

Figure 14: Obtained trajectories from the image processing analysis. Presented data are trajectories of the cylindrical firebrand models with longitudinal aspect ratio $\eta = 4$. From left to right, the reference velocities of the wind tunnel boundary layer are 1.79, 2.23, and 2.85 (m/s), and from top to bottom, the jet centerline velocities are 8.05, 9.0, and 12 (m/s).

sults corroborate the physical expectations, namely, by increasing the boundary layer reference velocity (U_0) for a given jet exit velocity ($U_{j|r=0}$) and aspect ratio (η), model firebrands tend to have lower rise height and land further downwind.

Characteristic lengths can be extracted from each trajectory, which include the maximum rise height (z_{max}), and the maximum downwind distance (x_l). Since the velocity field of the fire plume is modeled as a jet, the dominant length scale for the jet in a non-uniform boundary layer cross flow is the jet momentum length z_m ; see Tohidi and Kaye [51]. The momentum length represents the vertical distance at which a pure point source jet will have a mean vertical velocity equal to the mean horizontal velocity of the boundary layer [51]. In wind tunnel

Figure 15: Obtained trajectories from the image processing analysis. Presented data are trajectories of the cylindrical firebrand models with longitudinal aspect ratio $\eta = 6$. From left to right, the reference velocities of the wind tunnel boundary layer are 1.79, 2.23, and 2.85 (m/s), and from top to bottom, the jet centerline velocities are 8.05, 9.0, and 12 (m/s).

experiments, this length scale can be easily obtained by finding the height of the intersection point between the vertical (stream-wise) velocity profile of the jet at its centerline and the horizontal velocity of the boundary layer. In the case of a real fire plume the analogous length scale is the buoyancy length, z_f [51]. The buoyancy length is the distance from source at which a pure point source plume will have a mean vertical velocity equal to the mean horizontal velocity of the cross-flow boundary layer; For more details on the significance of z_m and z_f on wildfires' flow field see Tohidi and Kaye [51]. As z_m is the dominant length scale of the jet in non-uniform boundary layer cross-flow, it is used to normalize the maximum rise height and the maximum downwind distance. These data are summarized in figures 16-17 where the empirical (kernel) probability den-

370 sity functions of each parameter are shown for the tests under the same initial
 371 conditions.

Figure 16: Shown are the empirical (kernel) probability density functions (PDF) of z_{max}/z_m for different aspect ratios, under various initial conditions of the wind tunnel experiments. From left to right, U_0 is constant while $U_{j|r=0}$ is increasing. From top to bottom, U_0 is increasing and $U_{j|r=0}$ is constant.

371

372

373 Figure 16 illustrates variations of the normalized maximum rise height of the
 374 model firebrands with different aspect ratios subjected to various initial condi-
 375 tions of the wind tunnel experiments. As can be seen, for low U_0 as $U_{j|r=0}$
 376 increases the mean increases as well as its standard deviation. The foregoing

Figure 17: Shown are the empirical (kernel) probability density functions (PDF) of x_l/z_m for different aspect ratios, under various initial conditions of the wind tunnel experiments. From left to right, U_0 is constant while $U_{j|r=0}$ is increasing. From top to bottom, U_0 is increasing and $U_{j|r=0}$ is constant.

discussion is valid for the moderate boundary layer velocity as well. However, for high U_0 , increasing $U_{j|r=0}$ increases the mean but the standard deviation of z_{max}/z_m is relatively unchanged. Interestingly, maximum rise height of the cubic firebrand models show a bimodal distribution, particularly in cases with low to moderate boundary layer reference velocities (though this may be an artifact of the DOF in the tests).

Figure 18: Shown are the empirical (kernel) probability density functions (PDF) of x_l/z_{max} for different aspect ratios, under various initial conditions of the wind tunnel experiments. From left to right, U_0 is constant while $U_{j|r=0}$ is increasing. From top to bottom, U_0 is increasing and $U_{j|r=0}$ is constant.

384 As for of the normalized maximum downwind distance shown in figure 17,
385 in the low wind conditions, i.e. $U_0 = 1.79 \text{ (m/s)}$, increasing the jet velocity in-
386 creases the mean. However for firebrands with $\eta = 1, 4$ it does not significantly
387 increase the standard deviation. Quite the contrary, for the largest aspect ratio,
388 increasing the jet velocity not only increases the mean and standard deviation of
389 x_l/z_m but also leads to bimodal distribution of the normalized landing location
390 in some cases. The bimodal ground-distribution of firebrands has been reported

391 previously by Sardoy et al. [39]. For moderate to high wind conditions of the
392 experiment, increasing the jet velocity causes the model firebrands to loft higher
393 and subsequently travel further downwind.

394

395 The most striking result emerges when the maximum downwind distance
396 (x_l) is normalized by the maximum lofting height (z_{max}). Despite different de-
397 grees of freedom for each aspect ratio, PDFs of x_l/z_{max} are very similar. In
398 fact for a given velocity field, PDFs of different aspect ratios collapse on each
399 other. As can be see on figure 18, for a given boundary layer velocity, increasing
400 the jet speed does not result in a significant change in the mean and standard
401 deviation. However, for a given jet speed, an increase in the boundary layer
402 velocity increases the mean and standard deviation. This is further shown by
403 figure 19 where the maximum landing location (x_l) is plotted against the maxi-
404 mum rise height (z_{max}) for all released model firebrands during the wind tunnel
405 experiments. Clearly, there is a strong positive correlation between x_l and z_{max} .

406

407 Similarity of x_l/z_{max} PDFs and the observed positive correlation signify the
408 fact that there is a relationship, even though geometric, between the maximum
409 rise height and the maximum downwind distance of a firebrand traveling through
410 a given velocity field. Therefore, previous studies [52, 20, 41, 40, 39, 13, 43] in
411 which firebrands or debris are released from a fixed arbitrary height should be
412 careful about the justification of the chosen release heights as the maximum
413 rise height of firebrands will have significant influence on the modeled flight dis-
414 tance. Another implication of these results is that for mathematical modeling
415 of the lofting and downwind transport of firebrands/debris, lofting cannot be
416 decoupled from the transport through the atmospheric boundary layer.

417

Further insight may be obtained by summarizing the experimental param-
eters and conditions in terms of non-dimensional groups embedded in the physics

Figure 19: Scatter plot of the maximum landing location (x_l) against the maximum rise height (z_{max}) for all resolved trajectories during the experiments. Here, μ denotes the average and σ shows the standard deviation.

of the problem. The controlling non-dimensional groups are

$$\frac{U_0}{U_{j|r=0}}, \quad \eta, \quad \text{and} \quad \Omega = \frac{\rho_a U_0^2}{\rho_s g L_z}$$

where, as mentioned before, $U_0/U_{j|r=0}$ is the ratio of the boundary layer reference velocity to the jet centerline velocity at the exit, and η is the aspect ratio of the model firebrands. The additional parameter Ω is the Tachikawa number which is the ratio of the aerodynamic forces to the gravity force [22]. Here, Ω is calculated based on the largest projected area of the firebrands (the largest dimension, i.e. L_z). Respectively, ρ_a and ρ_s are density of the ambient air and the model firebrands. Since the combustion effects are decoupled from the

lofting and downwind transport in these experiments, ρ_s is constant. In fact, the time scale for a given flight in our experiments is small (approximately 1 – 2 seconds) such that any mass loss, were the model firebrands combusting, would be very small and have negligible impact on the flight dynamics. Given that the important variables x_l , z_{max} , and the jet momentum length scale (z_m) can be obtained from the measured velocity profiles, the results can be presented as

$$\left(\frac{x_l}{z_m}, \frac{z_{max}}{z_m} \right) = \Pi \left(\frac{U_0}{U_{j|r=0}}, \eta, \Omega \right). \quad (2)$$

418

419 Figure 20 shows variations of the mean (μ) and standard deviation (σ) of x_l/z_m ,
 420 z_{max}/z_m , and x_l/z_{max} against Ω . As shown, by increasing Ω , i.e. greater
 421 boundary layer reference velocity or smaller L_z , the mean of x_l/z_m and x_l/z_{max}
 422 increases. Also, the greater the aspect ratio, the greater the rate of increase in
 423 the mean and standard deviation of x_l/z_m , and x_l/z_{max} ; see figure 20 top &
 424 bottom. Also, the results suggest that the sensitivity of x_l to the change in the
 425 velocity field is higher for larger aspect ratios. However, the mean and standard
 426 deviation of the normalized rise height (z_{max}/z_m) tend to increase with very
 427 mild slopes as Ω increases, see figure 20 middle.

428

429 The distribution of the mean and standard deviation of x_l/z_m and z_{max}/z_m
 430 within the parameter space of the experiments, given in equation 2, are pre-
 431 sented by interpolated surfaces between the experimental results for each aspect
 432 ratio. These results are shown in figures 21-23. The results of $\eta = 1$ & 6 satisfy
 433 the physical expectations, in that for a given aspect ratio and boundary layer
 434 reference velocity ($\Omega = \text{const.}$), increasing the velocity ratio (decreasing the jet
 435 velocity) decreases the maximum rise height and subsequently the maximum
 436 downwind distance. Also, for a given wind velocity ratio ($U_{j|r=0} = \text{const.}$) in-
 437 creasing Ω increases the applied aerodynamic forces on the brands and leads to
 438 greater flight distances. Alternatively, results of $\eta = 1$ & 6 can be interpreted as
 439 traveling along characteristic curves (gradients of the contours) from any point
 440 on the parameter space leads to increasing aerodynamic forces either due to jet

or boundary layer and would increase the rise height or maximum downwind distance, respectively. However, results of model firebrands with aspect ratio $\eta = 4$ do not follow this trend, and there are lot of variability in the statistics of their flight as can be seen on figure 22. Nevertheless, the characteristic curves of the contour plots for different aspect ratios seem to follow the same trend.

A summary of the wind tunnel experimental results are given in table 2. The experimental data base can be accessed online by contacting the lead author.

5. Conclusions

Results of the most extensive set of large scale wind tunnel experiments of the lofting and downwind transport of model firebrands are presented. The data serves as an invaluable resource for not only firebrand transport studies but also for the flight of rod-like debris/brands through other velocity fields generated by extreme events such as hurricanes and storms. Full trajectories of the model firebrands were captured utilizing the developed image processing algorithm. From the captured trajectories, the maximum rise height and landing location of the model firebrands were obtained. It is shown that, given the velocity field, the maximum landing locations normalized with the maximum rise heights (x_l/z_{max}) have similar probability density functions (PDF) regardless of the firebrands' aspect ratio. This implies that, in modeling firebrand shower and the subsequent fire spotting phenomenon, unlike some previous studies, the lofting and downwind transport of the firebrands cannot be decoupled, since the maximum rise height significantly affects the ground distribution of firebrands.

The experimental results are presented in terms of the non-dimensional parameters, i.e. velocity ratio, aspect ratio, and Tachikawa number (Ω). It is shown that there is a strong positive correlation between the Tachikawa number and the mean and standard deviation of the landing locations, normalized with z_m and z_{max} . However, a very weak correlation between Ω and the statis-

Table 2: Summary of the wind tunnel experiments' results. Here, μ denotes the mean and σ shows the standard deviation of the data.

U_0 (m/s)	$U_{j r=0}$ (m/s)	η	μ_{x_l} (mm)	σ_{x_l} (mm)	$\left(\frac{\sigma}{\mu}\right)_{x_l}$	$\mu_{z_{max}}$ (mm)	$\sigma_{z_{max}}$ (mm)	$\left(\frac{\sigma}{\mu}\right)_{z_{max}}$
1.79	9.00	1	686.55	309.96	0.45148	363.17	130.67	0.3598
		4	1190.3	520.04	0.43688	513.17	186.99	0.36439
		6	757.4	481.36	0.63554	332.03	158.2	0.47645
	8.05	1	635.51	286.95	0.45153	308.09	114.38	0.37124
		4	1045.8	544.23	0.5204	477.89	176.62	0.36958
		6	551.56	393.15	0.7128	233.34	113.46	0.48625
	12.00	1	1339.3	463.26	0.34589	564.53	139.03	0.24627
		4	1307.7	464.54	0.35523	559.45	159.25	0.28465
		6	970.71	832.62	0.85774	438.83	228.86	0.52152
2.23	9.00	1	841.86	407.86	0.48447	297.2	129.52	0.43579
		4	1280.9	454.2	0.3546	463.64	156.96	0.33855
		6	1076.8	469.5	0.43602	353.11	122.55	0.34706
	8.05	1	913.75	266.59	0.29176	311.13	80.788	0.25966
		4	842.21	332.98	0.39536	276.5	98.743	0.35712
		6	996.58	428.5	0.42997	301.43	125.65	0.41683
	12.00	1	1489.4	448.77	0.30132	496.92	132.4	0.26644
		4	1651.2	763.61	0.46245	527.31	146.77	0.27834
		6	1766.7	565.31	0.31998	532.51	138.09	0.25933
2.85	9.00	1	1386.4	374.92	0.27043	373.04	96.265	0.25806
		4	1556.3	705.6	0.45338	390.62	140.88	0.36065
		6	1282.2	549.97	0.42892	296.63	122.84	0.41412
	8.05	1	1167.3	397.23	0.34031	308.28	106.23	0.34458
		4	1315.5	412.66	0.31368	332.58	96.826	0.29114
		6	1146.1	555.42	0.48461	262.17	104.28	0.39776
	12.00	1	1980.5	474.42	0.23955	535.39	117.58	0.21961
		4	1953.1	1243.9	0.63692	448.98	134.06	0.29859
		6	2085.7	779.35	0.37366	491.38	134.84	0.27442

470 tics of the rise height normalized with z_m was found. The results show high
 471 variability indicating that lofting and downwind transport of non-combusting
 472 firebrands is likely extremely sensitive to the initial conditions of the release
 473 and to temporal and spatial variations of the ambient velocity field. Also, it
 474 is shown that the larger the aspect ratio of firebrands, the more sensitive their
 475 landing locations are to the change in the velocity field, particularly the applied
 476 aerodynamic force.

477

478 The results presented herein are not directly applicable to full scale wild-
479 fires. However, the observations and data have significant implications for the
480 modeling of firebrand transport in wildfires and the resulting predictions of spot
481 fire risk. First, even under controlled laboratory conditions, there is significant
482 variability and, therefore, uncertainty in firebrand flight trajectories. Second,
483 the flight distance is strongly dependent on the maximum lofting height and,
484 therefore, the lofting and wind driven transport components of firebrand flight
485 cannot be decoupled and the entire wind field must be modeled. Third, the
486 shape of the firebrands is important. The model firebrands were observed to ro-
487 tate and, at times, move transverse to the wind direction. Therefore, lift forces
488 are important in modeling firebrand flight and simplifying assumptions that
489 treat firebrands as compact debris with no rotational inertia or lift forces are
490 likely to miss significant flight dynamics and may under-predict the potential
491 flight distance of a given firebrand. Finally, firebrand flight models need to be
492 run for a large number of flights in order to establish a statistically significant
493 understanding of the probability distribution of firebrand landing locations and
494 resulting spot fire risk. Therefore, firebrand transport models should include a
495 coupled fire plume and atmospheric boundary layer three dimensional wind field,
496 appropriately shaped fire brands, and a firebrand aerodynamic force model that
497 accounts for drag, lift, and rotational forces and moments. Model approaches
498 that satisfy these criteria can then be validated using the experimental results
499 presented herein prior to being applied to full-scale fires.

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Figure 20: From top to bottom, illustrated are variations of the mean (left) and standard deviation (right) of x_l/z_m , z_{max}/z_m , and x_l/z_{max} of model firebrands with respect to Ω .

Figure 21: Contour plots of the mean x_l/z_m (left) and the mean z_{max}/z_m (right) for model firebrands with aspect ratio $\eta = 1$ within the parameter space of Ω - $U_0/U_{j|r=0}$

Figure 22: Contour plots of the mean x_l/z_m (left) and the mean z_{max}/z_m (right) for model firebrands with aspect ratio $\eta = 4$ within the parameter space of Ω - $U_0/U_{j|r=0}$

Figure 23: Contour plots of the mean x_l/z_m (left) and the mean z_{max}/z_m (right) for model firebrands with aspect ratio $\eta = 6$ within the parameter space of Ω - $U_0/U_{j|r=0}$

- 508 [1] Albertson, M. L., Y. Dai, R. Jensen, and H. Rouse (1950). Diffusion of sub-
509 merged jets. *Transactions of the American Society of Civil Engineers* 115(1),
510 639–664.
- 511 [2] Albini, F. A. (1962). Scattering of plane wave by inhomogeneous sphere
512 under born approximation. *Journal of Applied Physics* 33(10), 3032–3036.
- 513 [3] Albini, F. A. (1964). Approximate evaluation of slender radome performance
514 in hypersonic flight. *AIAA Journal* 2(3), 476–483.
- 515 [4] Albini, F. A. (1979). *Spot fire distance from burning trees : a predictive*
516 *model*. United States.
- 517 [5] Albini, F. A. (1981). *Spot fire distance from isolated sources : extensions of*
518 *a predictive model*. United States.
- 519 [6] Albini, F. A. (1983a). Transport of Firebrands by Line Thermals. *Combustion*
520 *Science and Technology* 32(5-6), 277–288.
- 521 [7] Albini, F. A. (1993, mar). Dynamics and modeling of vegetation fire. Obser-
522 vations. In *Proceedings of the Workshop on Fire in the Environment*, Berlin,
523 Germany, pp. 39. Publ by John Wiley & Sons Ltd.
- 524 [8] Albini, F. A. and R. G. Jahn (1961). Reflection and transmission of
525 electromagnetic waves at electron density gradients. *Journal of Applied*
526 *Physics* 32(1), 75–82.
- 527 [9] Albini, F. A. F. A. . (1983b). *Potential spotting distance from wind-driven*
528 *surface fires / Frank A. Albini*.
- 529 [10] Anthenien, R. A., S. D. Tse, and A. C. Fernandez-Pello (2006). On the
530 trajectories of embers initially elevated or lofted by small scale ground fire
531 plumes in high winds. *Fire Safety Journal* 41(5), 349–363.
- 532 [11] Barr, B. W. and O. Ezekoye (2013, jan). Thermo-mechanical modeling of
533 firebrand breakage on a fractal tree. *Proceedings of the Combustion Insti-*
534 *tute* 34(2), 2649–2656.

- 535 [12] Bell, W. G. (1971). *The Great Fire of London in 1666*. Greenwood Pub-
536 lishing Group.
- 537 [13] Bhutia, S., M. A. Jenkins, and R. Sun (2010, mar). Comparison of fire-
538 brand propagation prediction by a plume model and a coupled fire/atmosphere
539 large eddy simulator. *Journal of Advances in Modeling Earth Systems* 2, 4.
- 540 [14] Cermak, J. E. and N. Isyumov (1998). Wind tunnel studies of buildings
541 and structures. American Society of Civil Engineers.
- 542 [15] Fischer, H. B., E. J. List, R. C. Y. Koh, J. Imberger, N. H. Brooks, and
543 H. B. Fisher (1979). *Mixing in inland and coastal waters*. Academic.
- 544 [16] Gonzalez, R. C. (2009). *Digital image processing*. Pearson Education India.
- 545 [17] Gonzalez, R. C., R. E. Woods, and S. L. Eddins (2004). *Digital image*
546 *processing using MATLAB*. Pearson Education India.
- 547 [18] Gould, J., W. McCaw, N. Cheney, P. Ellis, I. Knight, and A. Sullivan
548 (2008). *Project Vesta: fire in dry eucalypt forest: fuel structure, fuel dynamics*
549 *and fire behaviour*. CSIRO PUBLISHING.
- 550 [19] Grayson, M., W. Pang, and S. Schiff (2012, mar). Three-dimensional prob-
551 abilistic wind-borne debris trajectory model for building envelope impact risk
552 assessment. *Journal of Wind Engineering and Industrial Aerodynamics* 102,
553 22–35.
- 554 [20] Himoto, K. and T. Tanaka (2005). Transport of disk-shaped firebrands in
555 a turbulent boundary layer author. In *the Eighth International Symposium*
556 *on Fire Safety Science*, pp. 18—23.
- 557 [21] Himoto, K. and T. Tanaka (2008). Development and validation of a physics-
558 based urban fire spread model. *Fire Safety Journal* 43(7), 477–494.
- 559 [22] Holmes, J., C. Baker, and Y. Tamura (2006). Tachikawa number: a pro-
560 posal. *Journal of Wind Engineering and Industrial Aerodynamics* 94(1), 41–
561 47.

- [23] Karimpour, A. and N. B. Kaye (2012, January). On the stochastic nature of compact debris flight. *J. Wind Eng. & Ind. Aero.* 100(1), 77–90.
- [24] Koo, E., R. R. Linn, P. J. Pagni, and C. B. Edminster (2012). Modelling firebrand transport in wildfires using HIGRAD/FIRETEC. *International Journal of Wildland Fire* 21(4), 396–417.
- [25] Koo, E., P. J. Pagni, D. R. Weise, and J. P. Woycheese (2010). Firebrands and spotting ignition in large-scale fires. *International Journal of Wildland Fire* 19(7), 818.
- [26] Lee, J. H. W. and V. H. Chu (2003). *Turbulent jets and plumes: A Lagrangian approach*. Springer.
- [27] Lee, S.-L. and J. Hellman (1969). Study of firebrand trajectories in a turbulent swirling natural convection plume. *Combustion and Flame* 13(6), 645–655.
- [28] Lee, S.-L. and J. M. Hellman (1970). Firebrand trajectory study using an empirical velocity-dependent burning law. *Combustion and Flame* 15(3), 265–274.
- [29] Lin, N., J. D. Holmes, and C. W. Letchford (2007, feb). Trajectories of Wind-Borne Debris in Horizontal Winds and Applications to Impact Testing. *J. Struct. Eng.* 133(2), 274–282.
- [30] Liu, Z., D. Prevatt, L. Aponte-Bermudez, K. Gurley, T. Reinhold, and R. Akins (2009). Field measurement and wind tunnel simulation of hurricane wind loads on a single family dwelling. *Engineering Structures* 31(10), 2265–2274.
- [31] Manzello, S. L., T. G. Cleary, J. R. Shields, A. Maranghides, W. Mell, and J. C. Yang (2008). Experimental investigation of firebrands: Generation and ignition of fuel beds. *Fire Safety Journal* 43(3), 226–233.

- 588 [32] Manzello, S. L., A. Maranghides, and W. E. Mell (2007). Firebrand gener-
589 ation from burning vegetation. *International Journal of Wildland Fire* 16(4).
- 590 [33] Manzello, S. L., A. Maranghides, W. E. Mell, T. G. Cleary, and J. C. Yang
591 (2006). Firebrand production from burning vegetation. *Forest Ecology and*
592 *Management* 234, S119–S119.
- 593 [34] Manzello, S. L., A. Maranghides, J. R. Shields, W. E. Mell, Y. Hayashi,
594 and D. Nii (2009). Mass and size distribution of firebrands generated from
595 burning Korean pine (*Pinus koraiensis*) trees. *Fire and Materials* 33(1).
- 596 [35] Mell, W. E., S. L. Manzello, A. Maranghides, D. Butry, and R. G. Rehm
597 (2010). The wildland–urban interface fire problem—current approaches and
598 research needs. *International Journal of Wildland Fire* 19(2), 238–251.
- 599 [36] Nielsen, H. and L. Tao (1965). The fire plume above a large free-burning
600 fire. In *Symposium (International) on Combustion*, Volume 10, pp. 965–972.
601 Elsevier.
- 602 [37] Richards, P. J. (2010). Steady Aerodynamics of Rod and Plate Type De-
603bris.pdf. In *17th Australian Fluid Mechanics Conference*.
- 604 [38] Richards, P. J., N. Williams, B. Laing, M. McCarty, and M. Pond (2008,
605 October). Numerical calculation of the three-dimensional motion of wind-
606 borne debris. *Journal of Wind Engineering and Industrial Aerodynam-*
607 *ics* 96(10), 2188–2202.
- 608 [39] Sardoy, N., J. L. Consalvi, a. Kaiss, a. C. Fernandez-Pello, B. Porterie, and
609 a.C. Fernandez-Pello (2008, aug). Numerical study of ground-level distribu-
610 tion of firebrands generated by line fires. *Combustion and Flame* 154(3),
611 478–488.
- 612 [40] Sardoy, N., J.-L. Consalvi, B. Porterie, and A. Fernandez-Pello (2007).
613 Modeling transport and combustion of firebrands from burning trees. *Com-*
614 *bustion and Flame* 150(3), 151–169.

- [41] Sardoy, N., J.-L. Consalvi, B. Porterie, and A. Kaiss (2006). Transport and combustion of Ponderosa Pine firebrands from isolated burning trees. In *2006 1st International Symposium on Environment Identities and Mediterranean Area, ISEIM, July 9, 2006 - July 12, Corte-Ajaccio, France*, pp. 6–11. Polytech’Marseille, Dept. of Mechanical Engineering, CNRS UMR 6595, Technopole Chateau-Gombert, 5 rue Enrico Fermi, 13453 Marseille, France: Inst. of Elec. and Elec. Eng. Computer Society.
- [42] Scaramuzza, D., A. Martinelli, and R. Siegwart (2006). A toolbox for easily calibrating omnidirectional cameras. In *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 5695–5701. IEEE.
- [43] Song, J., X. Huang, N. Liu, H. Li, and L. Zhang (2016). The Wind Effect on the Transport and Burning of Firebrands. *Fire Technology*.
- [44] Tarifa, C. S., P. P. Del Notario, F. G. Moreno, and A. R. Villa (1967). Transport and combustion of firebrands, final report of grants FG-SP-11 and FG-SP-146. *US Department of Agriculture Forest Service*.
- [45] Tarifa, C. S., P. Notario, and F. G. Moreno (1965). On the flight paths and lifetimes of burning particles of wood. In *Symposium (international) on combustion*, Volume 10, pp. 1021–1037. Elsevier.
- [46] Tavoularis, S. (2005). *Measurement in fluid mechanics*. Cambridge University Press.
- [47] Tohidi, A. (2016). *Experimental and Numerical Modeling of Wildfire Spread via Fire Spotting*. Doctoral dissertation, Clemson University.
- [48] Tohidi, A. and N. Kaye (2016a, November). Experimental & numerical modeling of non-combusting model firebrands’ transport. In *Bulletin of the 69th American Physical Society, Division of Fluid Dynamics*, Volume 61. American Physical Society (APS).
- [49] Tohidi, A., N. Kaye, and W. Bridges (2015). Statistical description of firebrand size and shape distribution from coniferous trees for use in Metropolis

- 643 Monte Carlo simulations of firebrand flight distance. *Fire Safety Journal* 77,
644 21–35.
- 645 [50] Tohidi, A. and N. B. Kaye (2013). The Sensitivity of Modeled Flight Dis-
646 tance to the Lofting to Transport Transition Criterion in Coupled Ember
647 Flight Models. In *12th Americas Conference on Wind Engineering*, Seattle,
648 WA, USA, pp. 433–448.
- 649 [51] Tohidi, A. and N. B. Kaye (2016b). Highly buoyant bent-over plumes in a
650 boundary layer. *Atmospheric Environment* 131, 97–114.
- 651 [52] Tse, S. D. and A. C. Fernandez-Pello (1998). On the flight paths of metal
652 particles and embers generated by power lines in high winds a potential source
653 of wildland fires. *Fire Safety Journal* 30(4), 333–356.