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Investigation of firebrand production from Douglas Fir

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International Master of Science in Fire Safety Engineering

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ABSTRACT

Firebrands are one of the leading mechanisms of spread during wildfire and WUI fires, where they can be transported on several kilometers ahead of the fire front, potentially creating new fires. Thus, a better understanding of the parameters affecting firebrand generation and characteristics is mandatory to develop better simulation models and to predict the “firebrand generation potential” of different vegetative fuels. The goal of this study was to understand the impact of the wind on the firebrand generation. The experiments were conducted inside a 11m-long wind tunnel with 2 variable speed fans. Trunks and branches from Douglas-Fir (*Pseudotsuga menziesii*) were dried and tested separately using a 30cm-by-30cm propane burner under wind velocities that ranged from 0.4 m/s to 2.0 m/s. For each experiment, the firebrands generated were collected using water filled pans with fine meshes inside. The mass and area distribution of the firebrands over the test section was measured using a load cell and MATLAB image processing. It was observed that the wind velocity has an important effect on the distribution of the firebrands and is mainly controlling the location where the firebrands landed. Moreover, the speed of the firebrands inside the test section was determined using an image processing tool. It appeared that both the wind and the fire plume have an impact on the speed and the trajectory of the firebrands. In addition, the experiments conducted in this work need to be continued and diversified to different vegetative fuels to fully understand and simulate firebrand generation.

RESUME

Les brandons enflammés sont les principaux mécanismes liés à la propagation des feux de forêt ou des brandons peuvent être transportés sur plusieurs kilomètres à l'avant du front de flamme, pouvant ainsi créer de nouveaux départs de feu. Une meilleure compréhension des paramètres influençant la génération et les caractéristiques des brandons enflammés est donc obligatoire pour développer de meilleurs outils de simulation et pour prédire le « potentiel de création de brandons » de différents types de végétaux. Le but de cette étude est de comprendre l'impact du vent sur la génération de brandons. Les expériences furent menées dans un tunnel à vent long de 11 mètres avec 2 ventilateurs à vitesse variables. Des troncs et des branches de « Sapin de Douglas » furent séchés et testés séparément en utilisant un bruleur à propane de dimensions 30 cm par 30 cm soumis à des vitesses de vent allant de 0.4 m/s à 2 m/s. Pour chaque expérience, les brandons générés furent collectés en utilisant des plats en aluminium remplis d'eau avec une fine maille en tissu placés à l'intérieur. La distribution de la masse et de l'aire des brandons sur la section de test fut analysée sous différentes vitesses de vent. Il a été observé que la vitesse du vent à un impact important sur la distribution des brandons et qu'elle contrôle principalement l'endroit où les brandons atterrissent. De plus, la vitesse des brandons a été analyse à l'intérieur de la section de test à l'aide d'un outil d'analyse d'image. Il est apparu que le vent et la colonne convective créée par le feu avaient un impact sur la vitesse et la trajectoire des brandons. De plus, les expériences menées dans cette étude doivent être poursuivies et diversifiées à d'autres végétaux afin comprendre pleinement et de simuler la création de brandons.

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1. Introduction

1.1 Problem statement

Large scale wildfire, especially at the Wildland Urban Interface (WUI) have increased a lot over the past few years [1,2,3]. One of the most recent and dramatical example is the Camp Fire that occurred in 2018 around the town of Paradise in California [4] where 85 civilians were killed and almost 20,000 structures were destroyed. This increasing trend of large-scale wildfire is expected to continue mainly because of the climate change. Firebrands are the leading cause of ignition of structures at the Wildland Urban Interface (WUI) and they are also a significant driver of wildfire spread [4]. Thus, understanding the processes of firebrand generation and transport is key to protect more efficiently the populations and to predict more accurately the fire spread of important fires. However, predicting the hazard associated with firebrands in wildfires is complicated because of the different parameters affecting the firebrand generation. Moreover, the development of simulation tools is limited by the lack of data and information available in terms of naturals fuels and the differences between the different types of vegetation. To increase the understanding of the different processes, an approach is required where the characteristics of the firebrands will be gathered and collected under well controlled and defined conditions such as the wind or the intensity of the fire. The experiments described in this study will tend to increase the understanding of the different processes and parameters controlling firebrand generation form natural fuels.

1.2 Objectives

The main objective of this thesis was to understand the impact of wind on the firebrand generation and distribution in a controlled environment and to acquire data on firebrand generation from Douglas Fir. The collection of such data is mandatory to develop empirical relationships that need to be implemented in simulations tools to accurately represent firebrand generation from different fuels under different conditions. Moreover, the experimental setup described later in this report needed to be tested to determine if it was able to produce reliable and coherent results on the firebrand generation. The final goal of this work was to define a standard protocol for further firebrand generation studies with a well-defined collection procedure applicable to experiments using other fuels.

The following work presents the results of a series of experiments focused in studying the generation of firebrands from 1 m tall Douglas-Fir (Pseudotsuga menziesii) trunks and from branches samples as a function of wind velocity and for a set fire exposure in the controlled setting of a large-scale wind tunnel. First, a description of the experimental design and the methodology will be given. Then, the different test parameters and the analysis methodology will be described. After that, the results of experiments, including the mass distribution, the characterization of the firebrands, and the firebrands speed will be presented. Finally, a critical analysis of the experiments and suggestions for several improvements to the test and analysis method will be given.

1.3 Literature review

The following literature review will tend to present the current knowledge on the firebrand generation, characteristics, and behavior related to our study.

The production of firebrands from vegetative fuels is a complex process (Fig.1) and is described in Manzello et al. [4]. Firebrands are primarily generated from burning wildlands fuels (trees, shrubs, branches) and wooden structures (roofs, structural members).

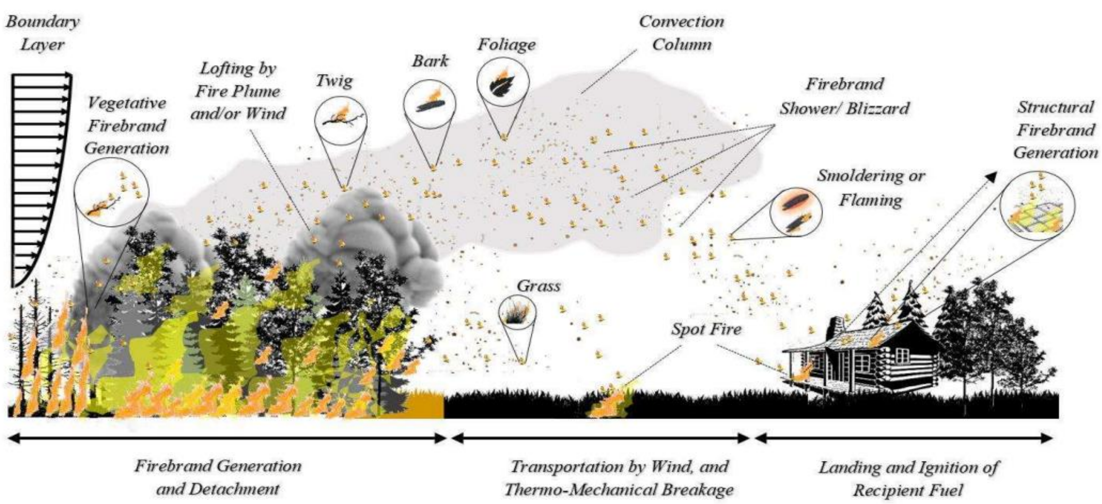

Fig. 1: Firebrand generation processes in wildland fire [15]

They are produced when the burning fuel thermally decomposes, loses structural integrity, and breaks down into smaller burning portions.

These smaller portions will eventually separate from the main structure due to the drag forces generated by the air flow surrounding the burning element. Then, they will be lofted in the air by the fire-induced buoyant plume and transported by the vertical forces created by the buoyant plume and the horizontal forces from the natural wind in a flaming or smoldering state as described in Tarifa et al. [5].

Furthermore, the ignition-by-firebrand potential depends on the amount of firebrands landing in the same area, the thermal properties of the recipient fuel (moisture content, thermal inertia, density) and the properties of the firebrands (temperature, size, mass) as explained in Deeming et al. [6]. Finally, the experiments conducted in Tarifa et al. [5] show the differences in term of firebrands generation depending on the fuel. It was observed that different types and species produced different amounts of firebrands with different characteristics.

Smaller scale laboratory experiments have also been conducted to understand the smaller mechanisms leading to firebrand generation such as the work of Hudson and Blunck [7] where a small vertical wind tunnel was built to determine the critical parameters where branches break off, or the experiments performed in Caton et al. [8] where the breakage mechanism of vegetative fuels was studied.

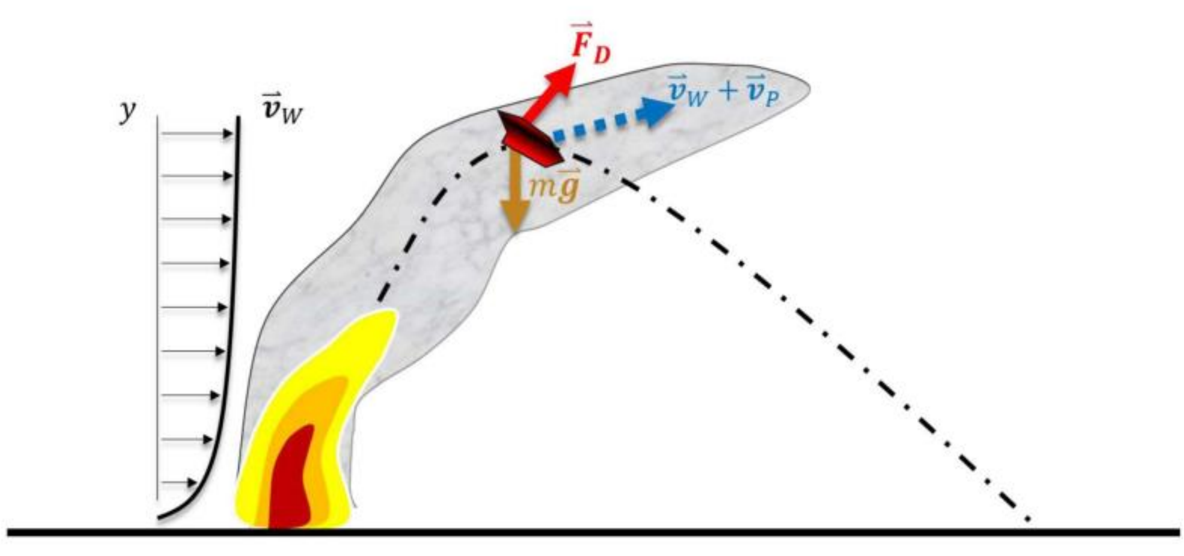

Fig. 2 : Schematic of firebrand trajectory formulation [4]

The trajectories of the firebrands are described in Fernandez-Pello [9]. A model is developed, consisting of the Applications of Newton's law of motion, and can be determined using the ballistic equations (Fig. 2). However, the fact that firebrands are combusting adds a level of complexity to the problem because their properties may change in time (temperature, size, and mass).

The moisture content of vegetative fuels is one of the most important parameters when it comes to firebrand generation as explained in the experiments conducted in Manzello et al. [10] and Baker [11]. These experiments are giving accurate fire characteristics of Douglas Fir and a range of firebrand production depending on the moisture content of the tree. For example, there is no generation of firebrands possible if the moisture content of the small branches and the needles is above 30%.

Several studies analyzed the characteristics of the firebrands such as their size, mass, and number from different types of vegetation in laboratory conditions such as the work of Manzello et al. [12,13], Suzuki et al. [14] or Babak [15]

Experiments have also been conducted in the field such as the work of El Houssami et al. [16], Koo et al. [17], Zen et al. [18], Filkov et al. [19]. These studies focused on the determination of the parameters affecting the firebrands characteristics and behaviors such as the environmental conditions or the characteristics of the fuel. Moreover, a collection methodology was developed in Thomas et al. [20].

Finally, multiple studies tried to model the transport of firebrands like the work of Koo et al. [21], Filkov et al. [22], Matvienko et al. [23] and Wickramasinghe et al. [24].

2. Methodology

2.1 Experimental setup

The wind tunnel used in these experiments is composed by a conditioning section, a test section, and a discharge section. The structure of the wind tunnel is shown in Fig. 3.

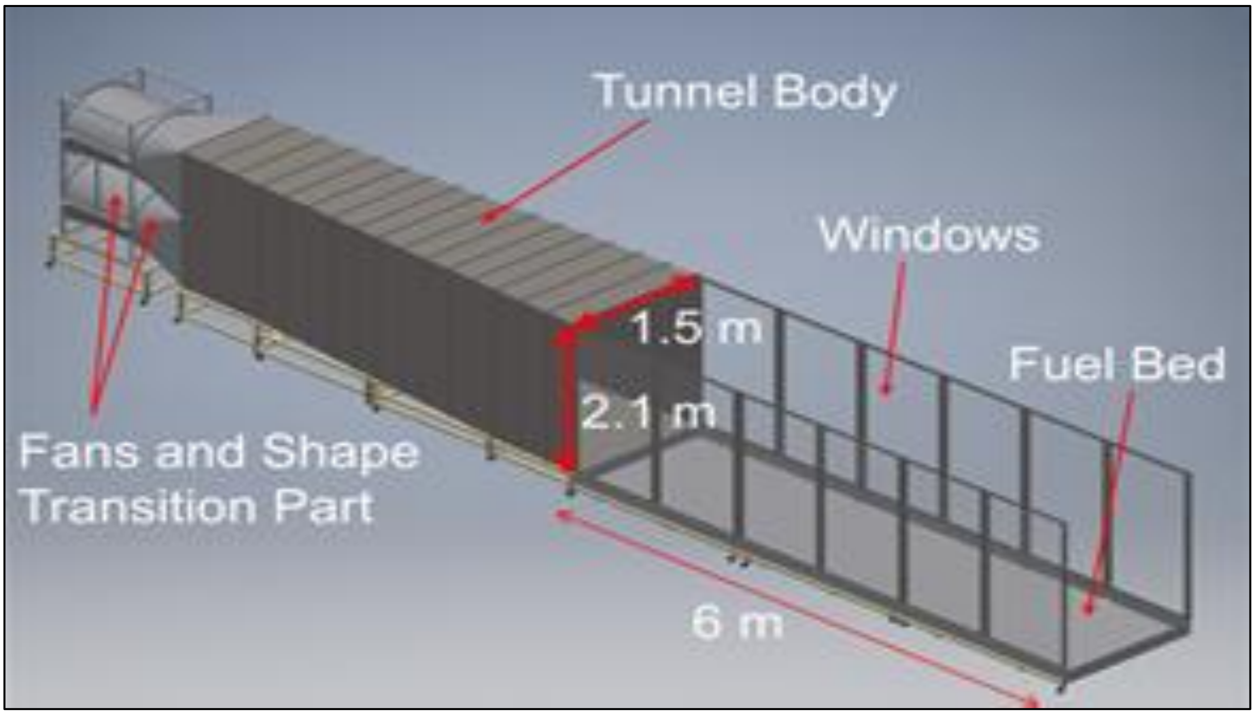

Fig. 3: Schematic of the wind tunnel

At the conditioning section, two variable speed fans, along with the diffuser and straighteners provide a stable and well-characterized inflow at the inlet of the test section. The 6m long test section is attached to the exit of the conditioning section and has a cross-sectional area of 1.5m (width) by 2 m (height). It is equipped with tempered windows for flow and flame diagnostics. Within the test section, a 1.5 m width by 6 m long test bed is placed (Fig. 4).

Fig. 4: Panoramic view of the test section of the wind tunnel

At the beginning of the test bed, a 30 cm-by-30 cm propane burner was installed. The heat release rate (HRR) of the burner was set by a mass flow controller regulating the volumetric flow of propane being delivered. The size of the burner was selected based on the maximum diameter of the samples, to ensure complete flame engulfment and avoid edge effects over the sample, as shown in Fig. 5.

Fig. 5: Flame engulfment on a trunk

Downstream of the burner, the vegetation sample is mounted over a 60 cm-by-45 cm platform, and held in place with a steel bracket, as shown in Fig. 7. For the experiments using the branches, a steel channel was used as a support for the branches as shown in Fig. 6.

Fig. 7: Holder setup for experiments using trunks

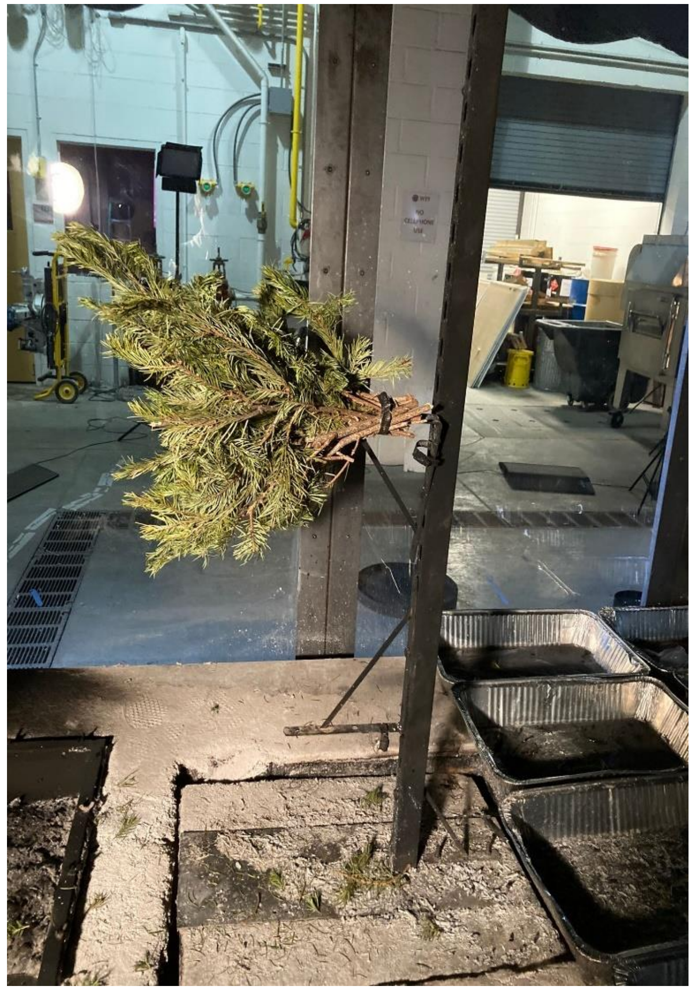

Fig. 6: Holder setup for expeirments using branches

A scale with a 0.2 g sensitivity sampling at 1 Hz was placed below the platform to record the mass loss of the sample during testing.

To collect the firebrands, a layout of 53 cm-by-33 cm aluminium pans was placed on the test section, downstream from the sample (Figs. 8 and 9).

These pans were filled with water to extinguish the firebrands when they land. A fine mesh (0.6 mm-by-0.6 mm grid size) was placed below the water level to easily collect the firebrands inside the pans after each experiment.

Fig. 8: Interior of the test section with the burner, the scale and the pans layout


Fig. 9: Interior of the test section with the trunk setup and the pans layout

At the discharge section, a deflector is placed to prevent the firebrands from escaping the confined test environment.

Three cameras were used to record the experiments and to track the firebrands:

- A high-speed DSLR camera placed on the side of the tunnel facing the glass panels was used to track the firebrands on the entirety of the test section

- A GoPro camera placed at the outlet of the test section was used to track the firebrands leaving the test section
- A GoPro camera placed close to tree, behind the glass panels, was used to record the ignition of the tree at the beginning of the experiments

After each experiment, the firebrands were collected, dried, and weighted using 0.01g accurate load cell to determine the mass distribution.

2.2 Fuel selection and drying procedure

For the current study, Douglas-Fir (*Pseudotsuga menziesii*) samples were used. The species was selected due to its geographical availability and the available data from past studies on this type of trees [10,25].

The moisture content inside vegetative fuels has a significant impact on the fire behaviour and the firebrand generation. A quantitative analysis on the effect of different moisture content values for vegetative fuels is given in [11]. Three different levels can be found (mass basis); With a moisture content of 70% or above, no sustain burning after the ignition will be observed and thus no firebrand generation. When the moisture content is between 30% and 70%, a transition regime occurs where the tree will be partially burned after the ignition. For moisture content below 30%, the tree will be fully consumed after the ignition and firebrand generation will occur. Moreover, Douglas Fir will not produce firebrand if the moisture content of its branches and needles is above 30% [10] (this value may slightly change depending on the experimental conditions).

The moisture content of trees when they were delivered in the laboratory was superior to 50%. Thus, a fuel conditioning chamber was built to reduce the moisture content of the trees used for the experiments (Figs. 10 and 11). The role of this chamber was to dry the wet firebrands after the experiments, to then characterize and analyze them. The chamber consisted in a 2.4 m by 1.2 m plasterboard box supported by a wooden structure. A 5000 W fan-forced heater was placed inside the box to dry the fuels. The exterior of the box was insulated with 4cm rock wool to minimise the heat losses. An operational temperature of 61°C was achieved inside the chamber.

Fig. 11: Interior of the conditionning chamber

Fig. 10: Outside of the conditionning chamber

The samples were prepared from locally-sources 2 m-tall live trees as follows:

First, the branches were separated from the trunks and stacked in different packages. Then, the trunks were cut in half to fit inside the test section, labelled and placed in the drying chamber. The moisture content and the weight of each trunk were checked every day to follow the evolution of the drying procedure.

Before testing, the moisture content was determined using a wood moisture meter able to measure the moisture content (volume basis) between 1.5% and 50 % with a +/- 2% accuracy. Through the drying procedure described above, the samples achieved a moisture content of 15% before testing.

For the experiments with the branches, packs of 200g were used.

A procedure was created to normalize the experiments and to help maintaining consistency for future work, particularly because this work provided preliminary results for a research grant received by WPI (see Appendix).

2.3 Flow Characterization

To determine the wind velocity inside the tunnel depending on the frequency of the two fans, the air flow had to be characterized. To do that, a 2m long steel tree with 8 pressure probes located on its length (Fig.12) was used.

Fig. 12: Steel tree with Pitot tubes used for the characterization of the air flow

The tree was moved at different locations inside the tunnel with fan frequencies going from 5 to 55 Hz, allowing us to determine the wind velocity at different height, length and width inside the tunnel.

The pressure probes measured the dynamic pressure in (Pa) caused by the air flow. All the data was then converted is speed (m/s) using Bernoulli's equation. Prior to that, the air density was determined using *Eq. 1*

$$\rho = \frac{P}{R \times T} \qquad \textit{Eq.1}$$

With:

ρ, the air density in kg/m^3

P, the absolute pressure in Pa

T, the absolute temperature in K

R, $287.058 J/kg\ K$ for dry air

Knowing the air density, *Eq. 2* was used to determine the wind velocity at each location:

$$V = \sqrt{\frac{2\Delta P}{\rho}} \times k \qquad \textit{Eq.2}$$

With:

V, the air velocity in m/s

P, the absolute pressure in Pa

ρ, the air density in kg/m^3

k, the Pitot tube correction factor (0.9)

2.4 Experimental matrix

Preliminary experiments were conducted to determine the most suitable HRR and wind velocities inside the tunnel. The different wind velocities selected are shown in Table 1. A HRR of 300 kW/m^2 was selected as it was the minimum HRR to achieve sufficient flame engulfment given the characteristics of the burner and the rest of the experimental setup. For each experiment, 3 repetitions were made.

Fuel Type	Wind velocity (m/s)	HRR (kW/m2)
Trunk	0.4	300
	1.0	
	2.0	
Branches	0.4	300
	1.0	
	2.0	

Table 1: Experimental matrix.

These parameters will have an important effect on the flame behavior, shape and on the firebrand production. The flame shape under 0.4 m/s and 1m/s wind speed are shown in Fig. 14 and Fig. 13. It appeared that with a 1m/s wind velocity, the flame was already tilted and close to the ground.

Fig. 13: Flame shape under 1 m/s wind velocity

Fig. 14: Flame shape under 0.4 m/s wind velocity

During the experiments, only the wind speed was modified. The branches and the trunks were tested separately to evaluate the difference in terms of firebrand production.

2.5 Mass and area distribution methodology

After being dried for several hours, the firebrands were weighted and pictured to analyze their mass and area distribution using MATLAB image processing. The procedure described in Hedayati et al. [26] was followed for the image analysis. The firebrands were placed on a white sheet of paper providing a contrasting background to black objects (firebrands in this case). The lighting setup consisted in 2 lights to avoid shadows. To automate the process and reduce the human uncertainty, a MATLAB code developed by Prof. James Urban, from WPI was used (see Appendix).

The first step of the analysis was to give a reference scale to the code. Measuring tapes were placed next to the firebrands before taking the picture (Fig. 15).

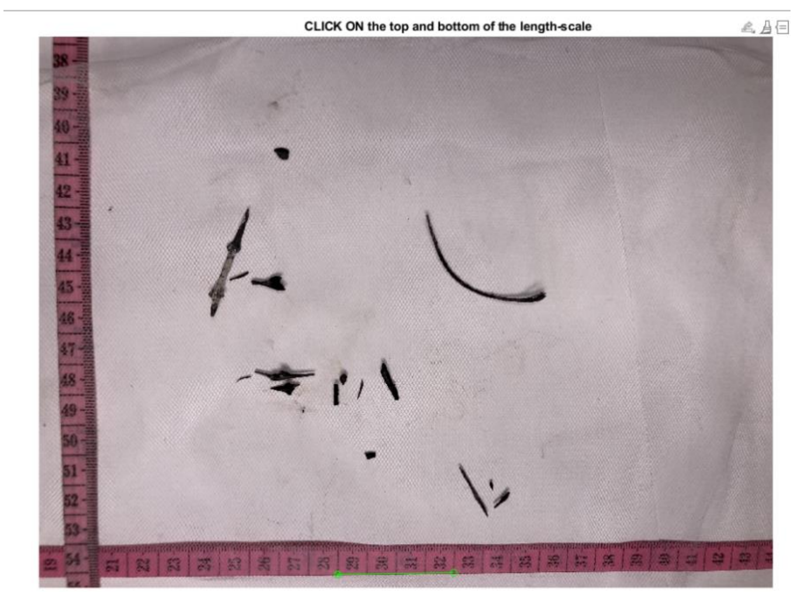

Fig. 15: Mesh full of firebrands used in MATLAB

Then, all the black bodies were changed to white bodies to determine their area in cm^2. All the red squares are delimiting the firebrands that are detected by MATLAB (Fig.16).

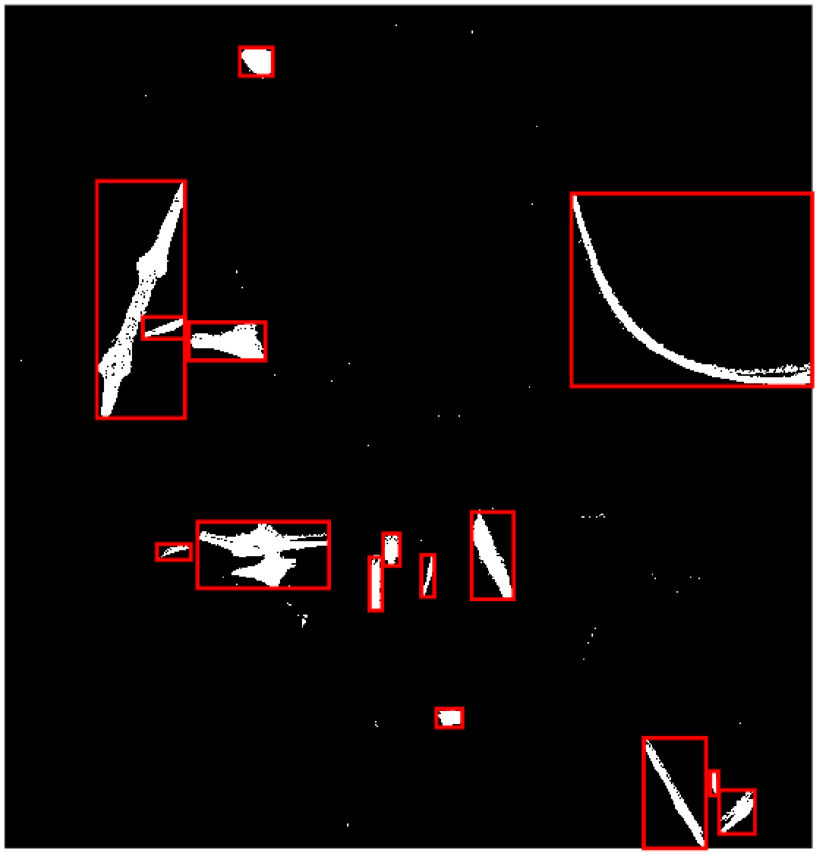

Fig. 16: Firebrands detection from MATLAB

Finally, the area of each firebrand detected was calculated and given by the code (Fig. 17).

```
The area of the firebrand 1 is: 0.030369cm^2
The area of the firebrand 2 is: 0.030788cm^2
The area of the firebrand 3 is: 0.040314cm^2
The area of the firebrand 4 is: 0.070759cm^2
The area of the firebrand 5 is: 0.080437cm^2
The area of the firebrand 6 is: 0.084134cm^2
The area of the firebrand 7 is: 0.12437cm^2
The area of the firebrand 8 is: 0.12784cm^2
The area of the firebrand 9 is: 0.1584cm^2
The area of the firebrand 10 is: 0.23918cm^2
The area of the firebrand 11 is: 0.31302cm^2
The area of the firebrand 12 is: 0.36911cm^2
The area of the firebrand 13 is: 0.73019cm^2
The area of the firebrand 14 is: 0.73956cm^2
The area of the firebrand 15 is: 0.93972cm^2
```

Fig. 17: Area of different firebrands calculated by MATLAB

2.6 Firebrand speed analysis

The velocity of the firebrands was determined using the recordings form a DSLR camera and MATLAB image processing. The first step of the analysis was to determine a reference scale in the vertical and horizontal directions (Figs. 18 and 19) Then, the videos were divided into frames by the MATLAB code (see Appendix). For each frame, the firebrands were manually detected and selected as shown in Fig. 20.

Fig. 18: Vertical lenght scale

Fig. 19: Horizontal lenght scale

Fig. 20: Firebrands selected for a single frame

3. Results

3.1 Visual analysis

The experiments conducted using trunks allowed us to observe that even at low moisture contents ranging from 5% to 10%, the bark of the trees was not producing firebrands and that the firebrands were only produced by the branches and needles located in the upper region. Instead of creating firebrands, the bark smouldered and created a char layer protecting the inside of the trunks.

Fig. 21: Smouldering on the bark of Douglas Fir trunk

The non-production of firebrands could be explained by different factors:

- The intrinsic characteristics of the tree:

  Even when dried to low moisture content, the Douglas Fir bark has a "smooth" structure which might not be suitable to produce large amount of firebrands.

- The experimental parameters:

  The parameters such as the wind velocity or the HRR could not be optimal to create firebrands from the Douglas Fir bark. Another factor could be the moisture content, which as explained before, is a critical parameter to create firebrands.

- Exposure time

  During our experiments, the vegetation was exposed to the fire for 4 minutes. This time might be too low to initiate the smouldering process and start to create firebrands from the bark.

3.2 Trajectory analysis

The experiments performed allowed us to verify if we were able to reproduce the theoretical trajectories and flights paths of firebrands with the current setup. It appeared that the trajectories followed the 3 stages of their transport described in [9]:

- The injection of the firebrands in the fire induced plume leading the firebrands to go up inside the tunnel:

Fig. 22: Firebrands going up due to the fire-induced plume

- The flight path of the firebrands in the test section:

Fig. 23: Firebrands travelling inside the test section

- The fall of the firebrands leading to the landing:

Fig. 24: Firebrands falling in the test section

Using Fig. 22, we can clearly see the effect of the buoyancy on the firebrands just after the detachment. Then as the firebrands are pushed away from the buoyant plume by the air flow, the effect of buoyancy is decreasing leading the firebrands to only move in the horizontal direction where only the air flow from the fans has an impact on their trajectory.

3. 3 Mass and area distribution

The analysis of the mass and area distribution for the 3 different wind speed are shown in Figs. 25, 26 and 27.

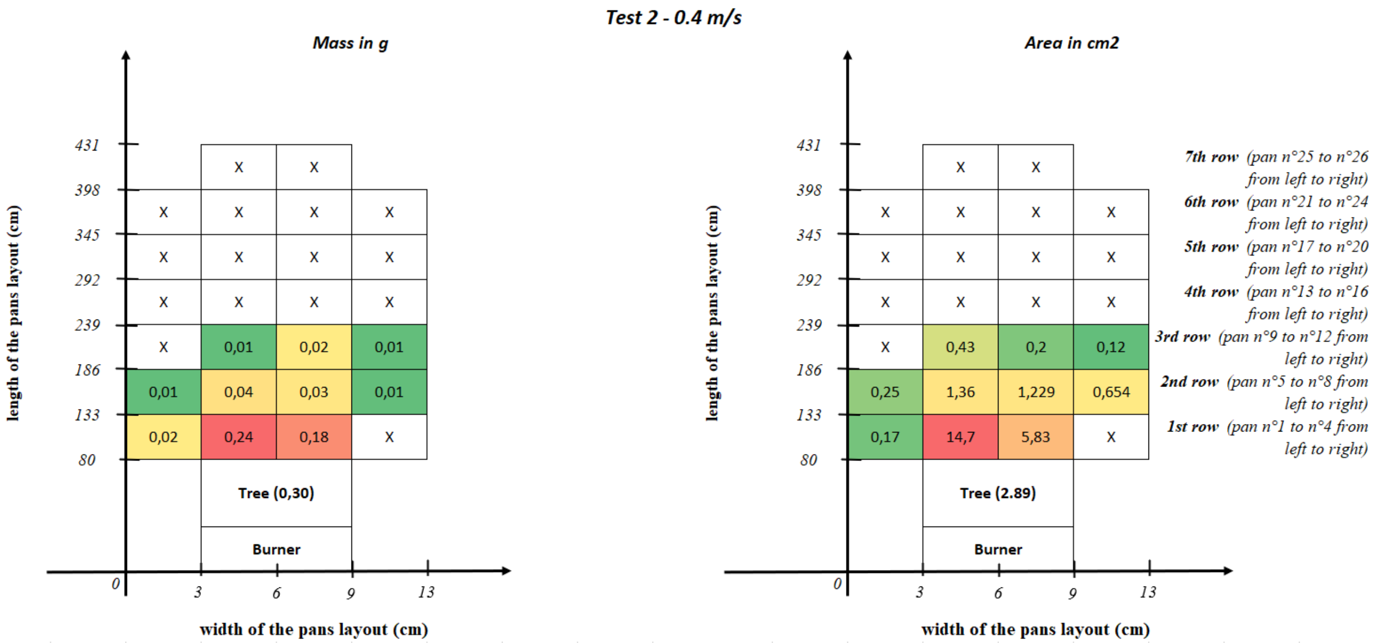

Fig. 25: Mass and area distribution for a 0.4 m/s experiment using branches

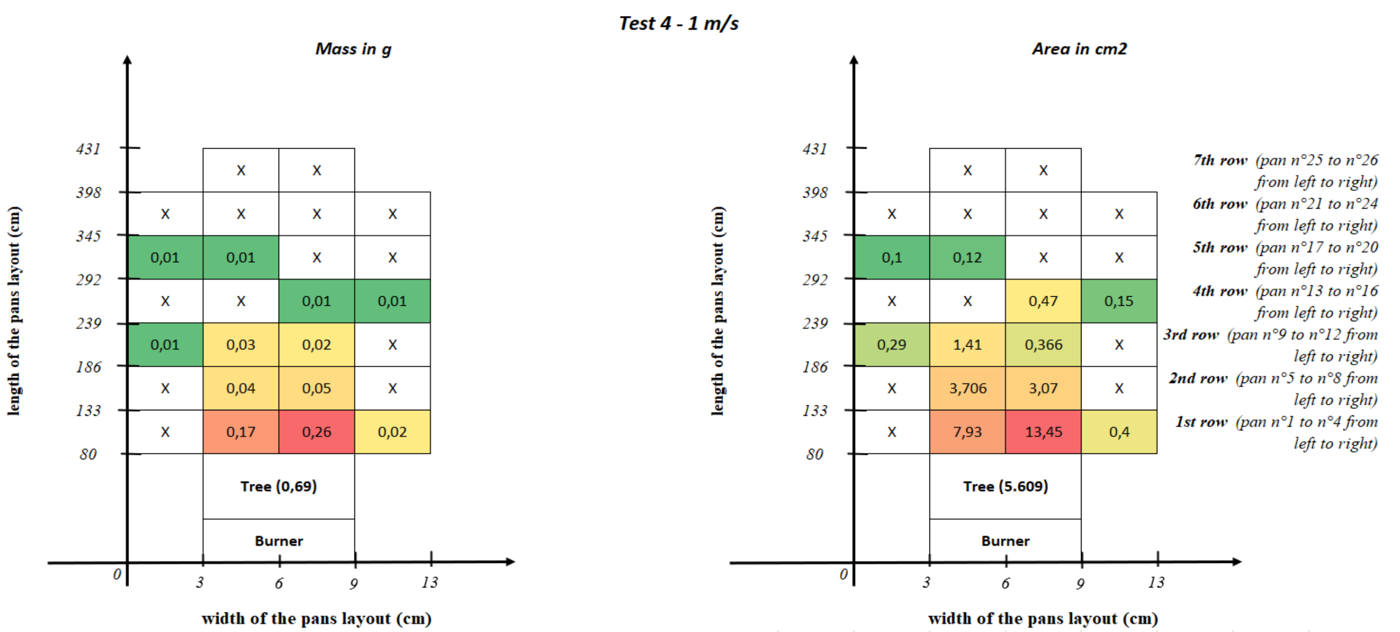

Fig. 26: Mass and area distribution for a 1 m/s experiment using branches

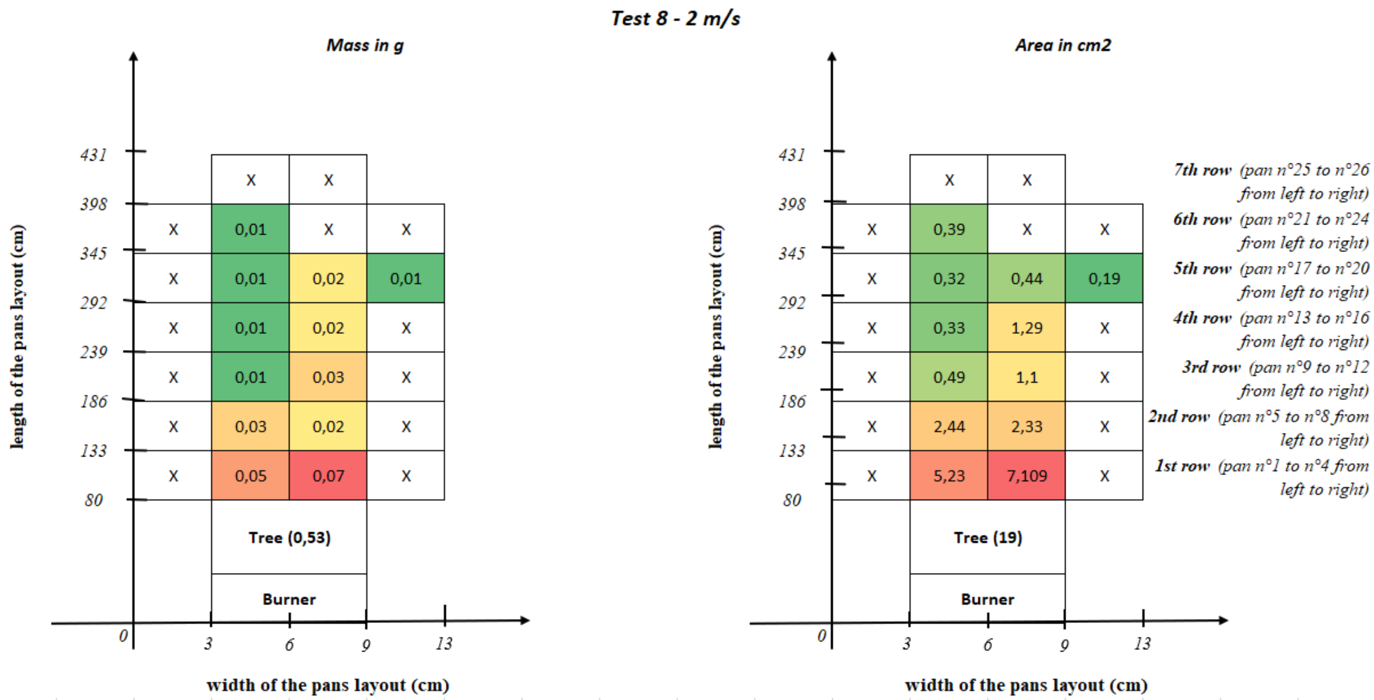

Fig. 27: Mass and area distribution for a 2 m/s experiment using branches

First of all, it is observed that the distribution of the firebrands in the pan layout is a function of the wind velocity. For a 0.4 m/s wind, the firebrands only landed in the first 3 rows of pans, but they were landing in every pan even on the sides. In this case, as the wind velocity was relatively low, the turbulence and the gravity played a major role in the spatial distribution. For the firebrands produced, the air flow was not strong enough to carry them far away from the vegetation sample. Thus, the firebrands were only landing in the first rows of pans.

When the wind velocity was increased to 1 m/s, the firebrands reached pans further away from the burner, however, they were not landing in the side pans near the burner but in the sides pans of the 4^{th} and 5^{th} rows.

Finally, with the wind velocity at 2 m/s, the firebrands only landed in the two middle columns of the pans layout. Under this last scenario, the air flow was strong enough to be the only driver of the firebrand flight paths. Thus, the firebrands were reaching the most far away pans. Moreover, it was observed that under a 2 m/s wind velocity, an important amount of firebrands were leaving the tunnel.

For the experiments using trunks, the same trends in term of spatial distribution are observed as shown in Figs. 28, 29 and 30.

However, the characteristics of the firebrands were different with heavier and bigger firebrands produced especially in the first row of pans. This trend comes from the fact that the branches that burned and produced firebrands during the experiments using trees were bigger than the branches tested during the other type of experiments.

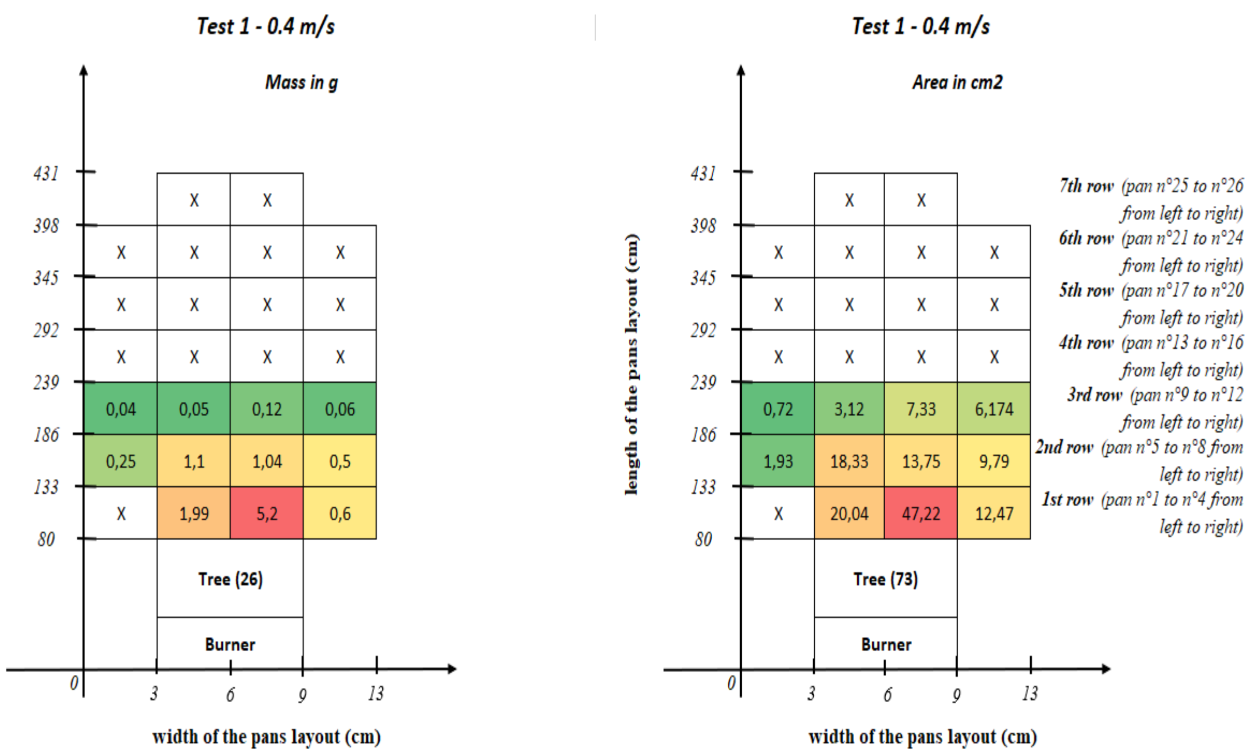

Fig. 28: Mass and area distribution for 0.4 m/s experiment using trunks

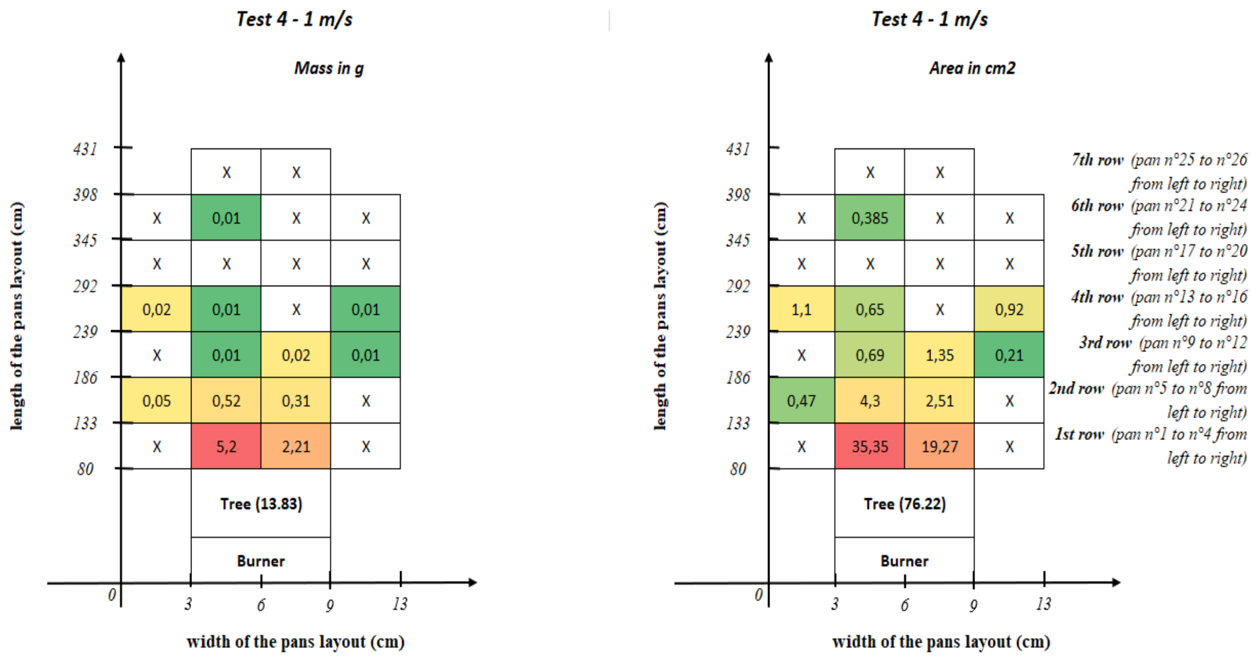

Fig. 29: Mass and area distribution for 1 m/s experiment using trunks

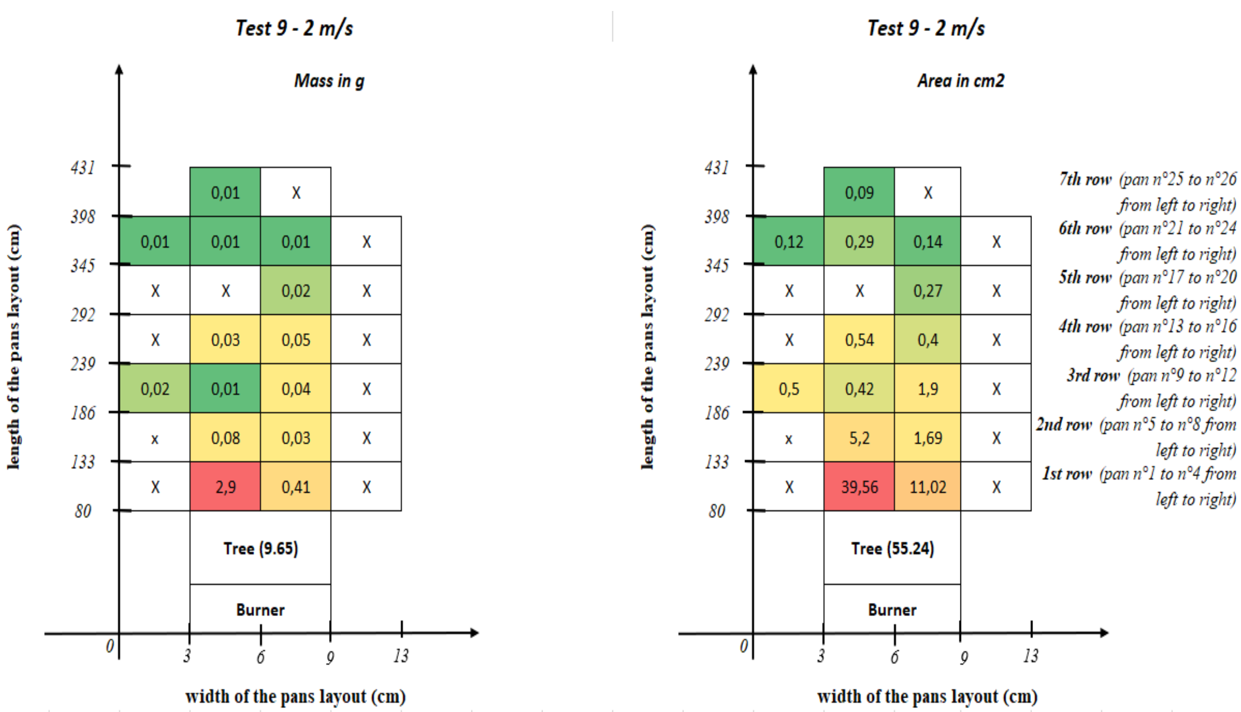

Fig. 30: Mass and area distribution for 2 m/s experiment using trunks

From the analysis of the mass and area distribution, it was also observed that a relationship existed between the mass and the area of the firebrands produced. As the mass increased, the area of the firebrand increased too. To confirm this trend, the mass and the area of the firebrands produced from different experiments were plotted as shown in Figs. 31, 32 and 33.

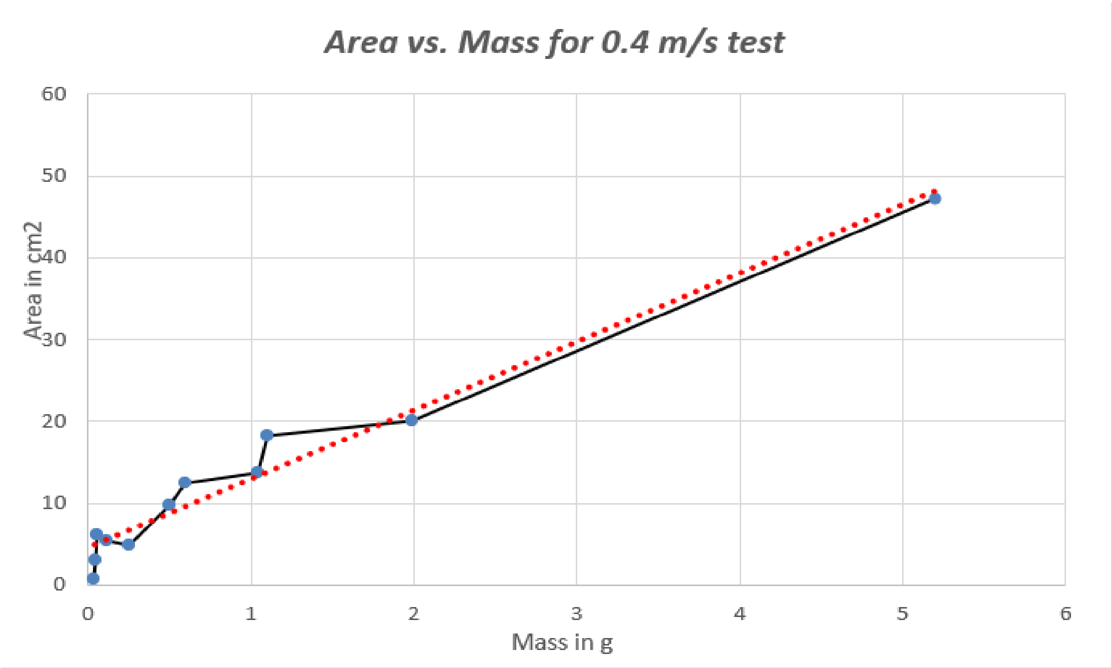

Fig. 31: Area and mass of the firebrands collected for 0.4 m/s experiment

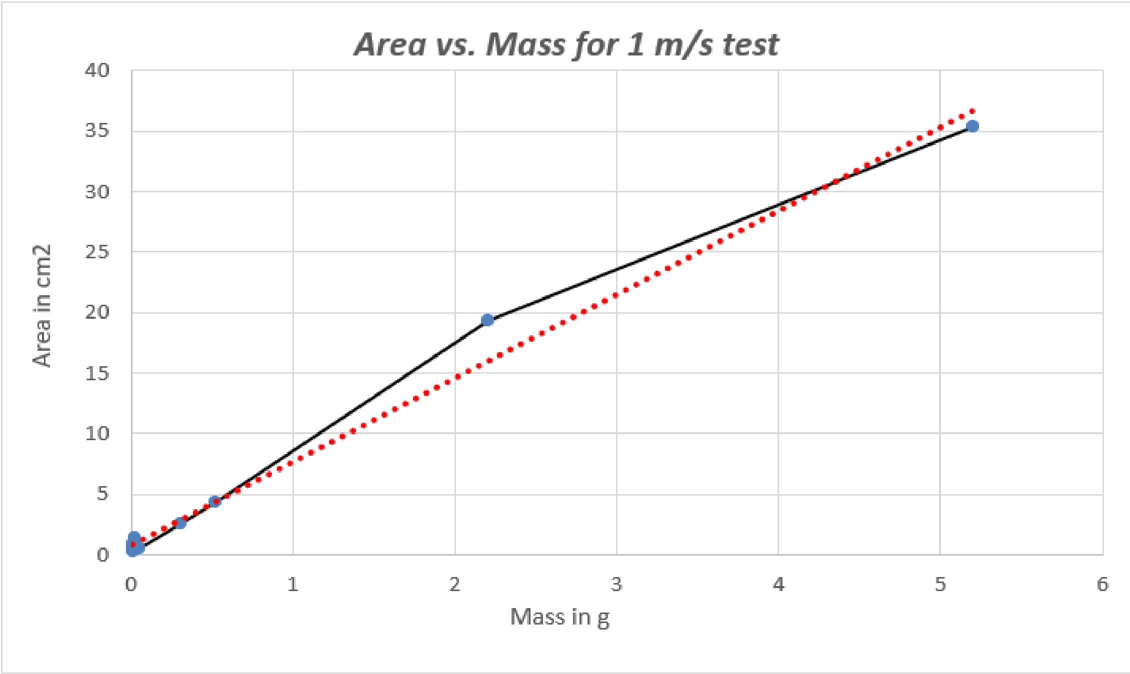

Fig. 32: Area and mass of the firebrands collected for 1 m/s experiment

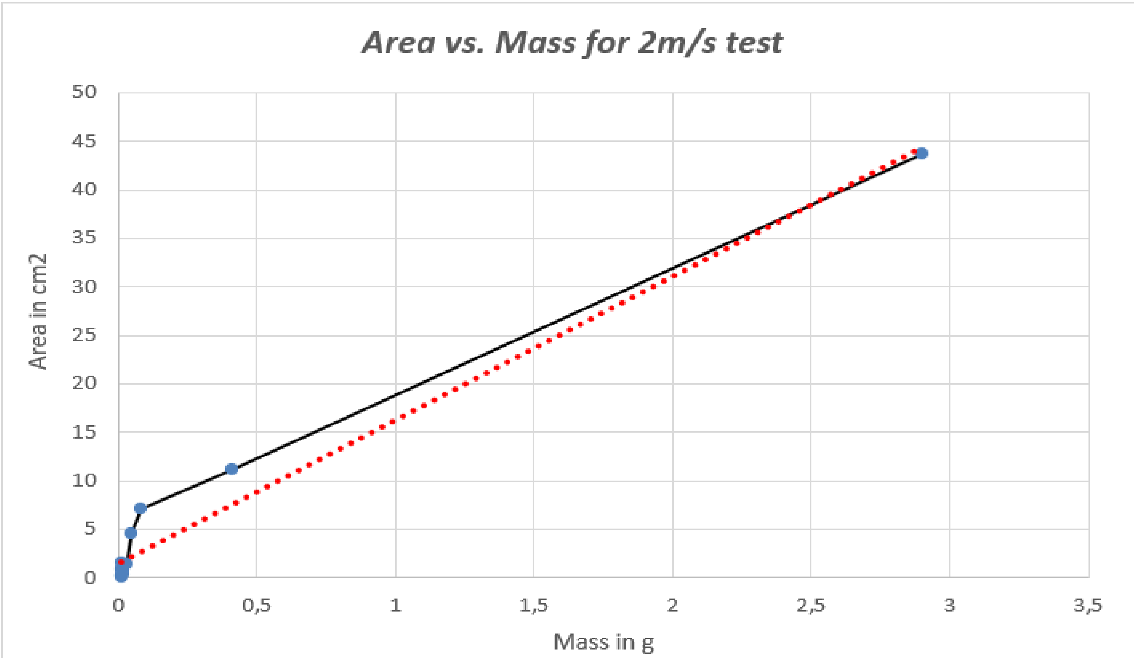

Fig. 33: Area and mass of the firebrands collected for 2 m/s experiment

3.4 Firebrand speed

The firebrand speed under the different wind velocities are shown in Figs. 34, 35 and 36.

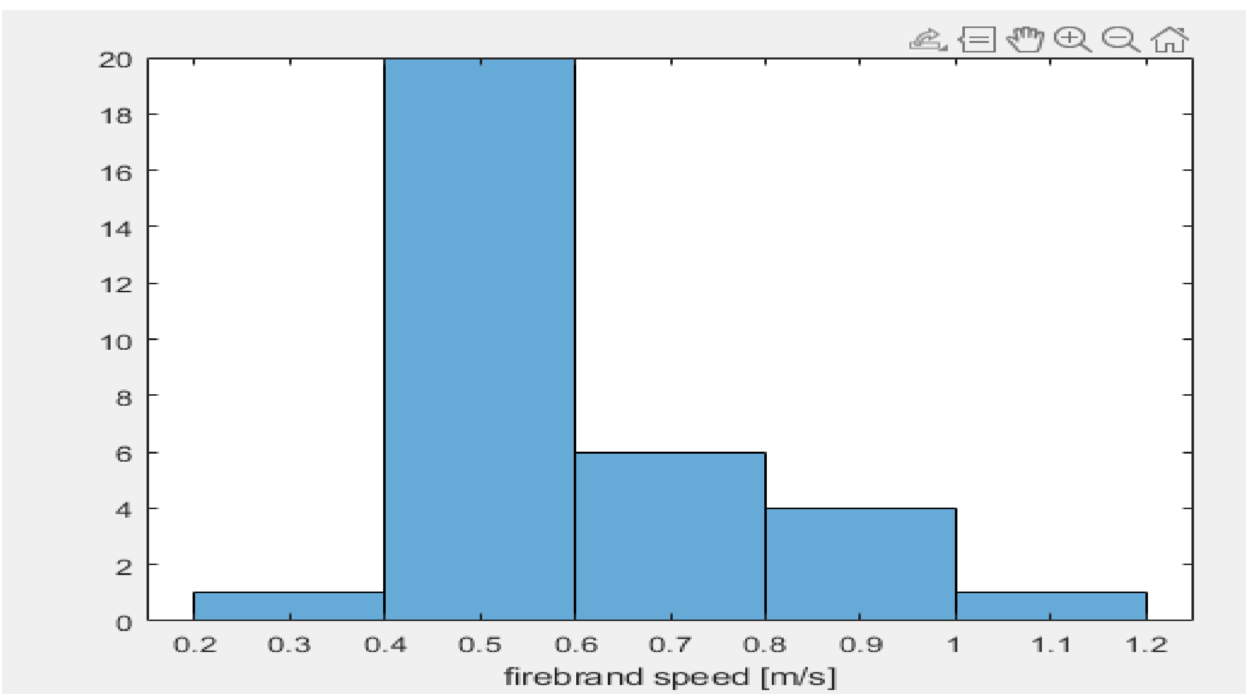

Fig. 34: Speed distribution of the firebrands under 0.4 m/s wind velocity

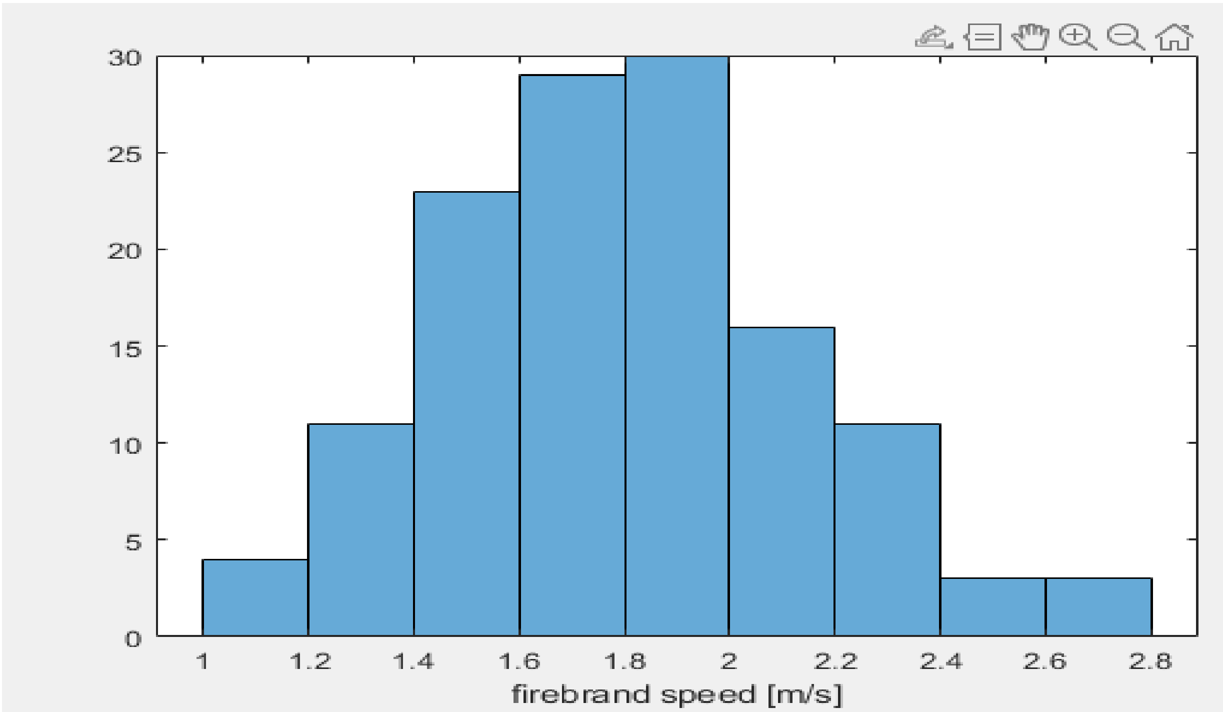

Fig. 35: Speed distribution of the firebrands under 1 m/s wind velocity

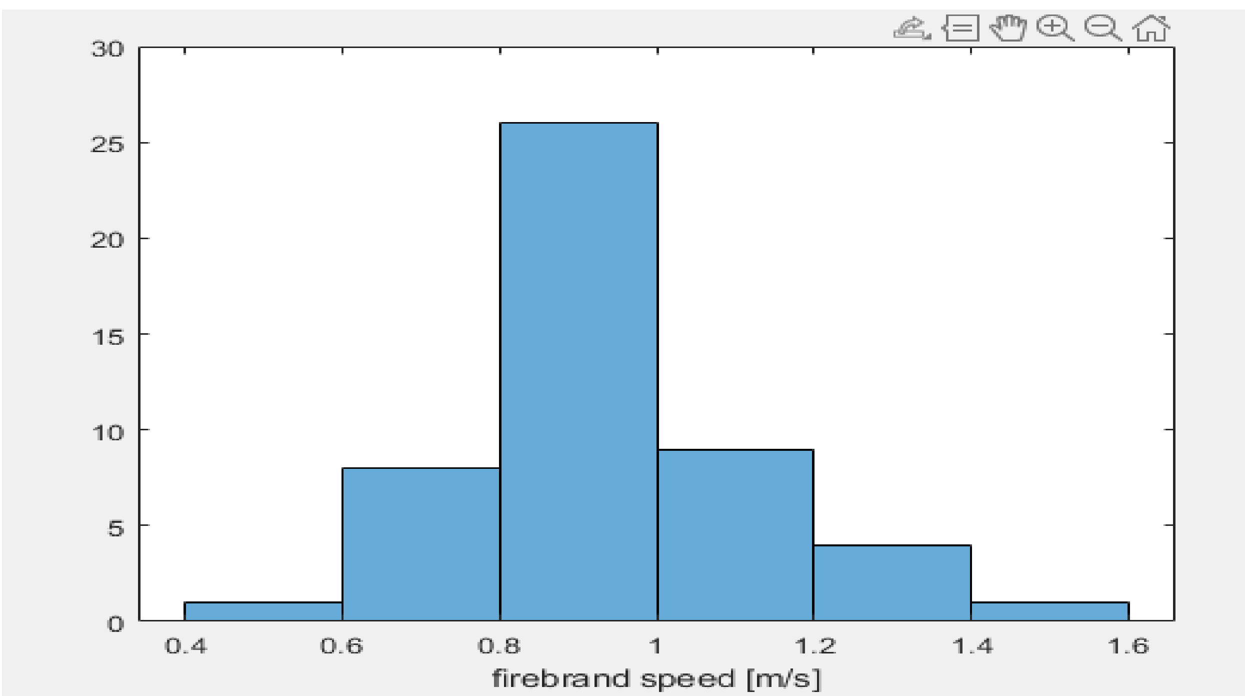

Fig. 36 : Speed distribution of the firebrands under 2 m/s wind velocity

It was observed that the speed of the firebrands is well correlated to the wind speed. In this analysis, only the absolute velocity of the firebrands was determined. This absolute velocity is composed by:

- The vertical velocity induced by the buoyancy
- The horizontal velocity induced by the air flow

The fluctuations of speed for each wind velocity are due to different parameters. The most obvious parameters are the size and the mass of the firebrands. For a given wind speed, the bigger and heavier firebrands are, the slower they'll be and the less distance they will be able to travel.

Another parameter is the buoyancy created by the fire plume. As explained before, one of the first steps in the firebrand transport is the injection of the firebrand in the fire plume. At this stage, the buoyancy created by the fire leads to an increasing speed in the vertical direction of the firebrands right after their detachment from the vegetation.

Finally, the turbulences created by the air flow will lead to a non-homogenous wind velocity inside the test section of the tunnel especially near the boundaries (ceiling, sides and top of the wooden platform).

3. 5 Mass loss rate and firebrand shower

As it was observed during the experiments, most of the firebrands were produced a few seconds after the ignition of the vegetation. This behavior is known as firebrand shower [27] and it is the main cause of building ignition at the WUI. This is mostly due to the large amount of firebrands produced and "thrown" at the construction material or inside the ventilation systems of buildings, causing rapid heating and leading to ignition.

Video and mass recordings were analyzed in parallel to determine if the sudden loss of mass happening a few seconds after the ignition was mainly due to the firebrand generation. It appeared that the firebrand shower phenomenon is happening at the same time as the sudden loss of mass.

Fig. 37: Firebrand shower phenomenom from a 2 m/s branches test

On the video recording, under a 2 m/s wind velocity, it is observed that the firebrand shower phenomenon is lasting for approximately 55 seconds, which is coherent with the mass loss rate recordings of the test where there is an important loss of mass happening at the same time (Fig. 38).

However, as shown in Figs. 25, 26 and 27, it appeared that the total mass of firebrands produced is small (25 g) compared to the total mass lost by the vegetation sample (200g). This means that most of the mass is lost through the flames and attached smoldering of the fuel. It also gives a first idea of the mass of firebrands produced per mass of vegetative fuel, in this case small branches from.

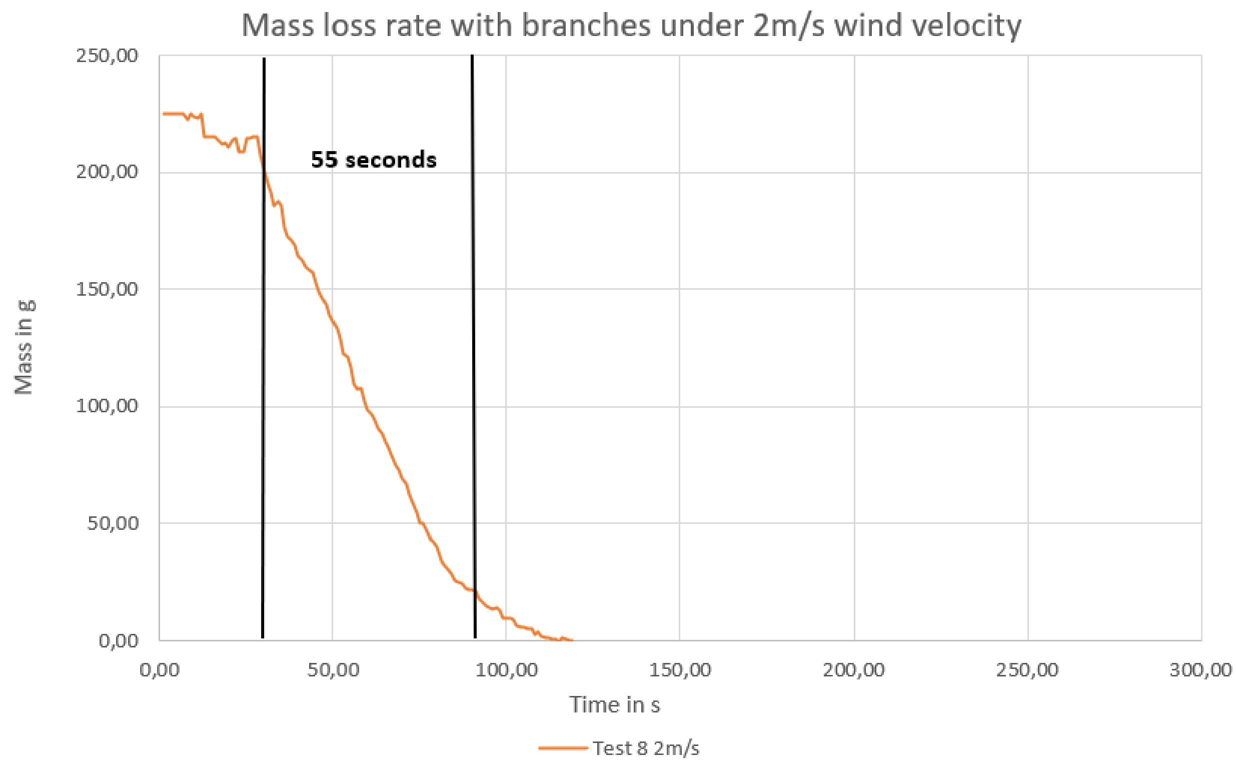

Fig. 38: Mass loss rate of an expeirments using branches under 2 m/s wind velocity

The different mass loss rate for the main burning period as a function of the wind speed are shown in Table 2.

Wind speed used in the experiments	0.4 m/s	1 m/s	2 m/s
Mass loss rate in g/s	**1,21**	**1,32**	**1,49**

Table 2 : Average mass loss rate as a function of the wind speed

It is observed that the mass loss rate is increasing with the wind speed. This mainly due to the better mixing of the pyrolysis gases and a more important pre-heating of the unburned fuel due to the tilt of the flame. This trend was also visually observed with bigger firebrand fluxes as the wind speed increased.

4. Discussion

4. 1 Results

The analysis conducted by [16] shows that 70% of the firebrands collected were generated from the bark of the vegetation. However, this was not the case for our experiments, where almost all the firebrands collected were produced from the branches and the needles of Douglas Fir. This important difference in the results could be explained by the fuel tested and/or the fire intensity.

The experiments conducted in [28, 14] show the same trends in terms of size and mass distribution from different types of vegetative fuels and from wooden construction materials. It means that the behaviors observed in our analysis are coherent and are not only related to firebrands from Douglas Fir.

The study performed in [19] is giving an analysis on the firebrands speed during a prescribed burning. It appeared that the firebrand speed was ranging from 0.1 m/s to 10.5 m/s with an average speed of 2.5 m/s. These results are coherent with the firebrand speed found in our analysis. The differences in the results are due to the different configuration of the experiments (field experiments in this case) and the intensity of the air flow used in their experiments.

4. 2 Uncertainties

A) Uncertainties related to the firebrands collection

The main uncertainties in the results come from the fact that we were not able to collect all the firebrands produced for each experiment is also an important uncertainty both for the firebrands distribution and also the mass loss rate analysis. For the distribution it means that our analysis might be uncompleted if an important amount of firebrand left the tunnel. For the mass loss rate analysis, it means that we do not have the total mass of firebrands produced and we cannot accurately compare the two.

B) Uncertainties related to the scales

The scale used for the mass loss rate recordings had a 1 Hz sampling rate which was not optimal to accurately analyze the mass loss rate of 200 g samples especially with the fast combustion process that we observed using the branches. The vibrations, caused by the wind, on the platform placed on top of the scale also led to uncertainties in the mass loss results. Moreover, the scale used for the weight distribution had a 0.01 g sensitivity which was still too inaccurate to determine the mass of the smaller firebrands produced (mainly from needles).

C) Uncertainties related to area distribution

Another uncertainty is related to the image analysis using MATLAB. The firebrands were illuminated using 2 powerful lights to create as few shadows as possible on the pictures. However, even with this setup some shadows appeared on several pictures. These shadow parts were then considered as a part of a firebrand when using the MATLAB code, thus leading to a larger area (+10% of the final area for the firebrands in some cases). This problem was then manually corrected but some minor uncertainties could still be present.

D) Uncertainties related to the firebrands speed

The analysis of the firebrand velocity also contained uncertainties. The speed was determined by using an image analysis of the video recordings and by manually clicking on the firebrands thus including human uncertainties in the accuracy of the "clicking". This uncertainty was evaluated at +/- 0.2 m/s Another important aspect is that the speed of the same firebrand was changing depending on its location inside the test section, leading to different results for the same firebrands at different time steps.

5. Conclusion

The effect of wind on the firebrand generation by Douglas Fir trunks and branches was studied using a 11 m long wind tunnel with a controlled wind velocity and heat release rate from the burner. The mass and area distribution of the firebrands under 3 different wind velocities were analyzed to determine the impact of the wind. It appeared that the wind velocity was the main driver of the firebrand distribution and different distribution patterns appeared depending on its intensity. The firebrand speed was also analyzed under the same wind conditions using MATLAB image processing. It was observed that both the wind velocity and the buoyancy from the fire had an impact on the firebrand speed and that the speed was ranging from 0.3 m/s to 2.6 m/s depending on the wind velocity used. Finally, the study of the mass loss rate and the video recordings showed that the sudden and important loss of mass from the samples a few seconds after the ignition was directly linked to the firebrand shower phenomenon where an important firebrand flux is produced.

A qualitative analysis of the uncertainties from the experiments was also given. It appeared that the results using scales were the ones containing the biggest uncertainties. Some uncertainties were also related to the experimental setup itself such as the fact that some firebrands left the tunnel during several experiments and that their analysis was not possible.

Further experiments using different types and species of vegetation are needed to increase the understanding of the different processes leading to firebrand generation and collet more data on other fuels.

5.1 Future work

In order to improve the analysis, further work could include the following:

- Change the parameters used

  Same experiments but changes in the wind velocity, the HRR and the moisture content to collect more data on firebrand generation from Douglas Fir under different conditions.

- Add new parameters

  As explained in [4] the ambient air temperature and hygrometry have an impact on the firebrand generation and behavior. However, with the setup described it was not possible to change these parameters to determine their actual impact.

  Another aspect to analyze is the firebrand temperature. By using IR cameras [30] or the color pyrometry method [29], the firebrand temperature depending on different conditions as well as the heat losses of the firebrands could be determined.

- Change the fuel type and species

  Using different types and species of vegetation would allow us to understand the differences in term of firebrand generation and characteristics from these species. The final goal being to create a “data base” for firebrand generation and to implement these results in simulations models.

- Determine the contribution of the buoyancy to the firebrand speed both in the vertical and horizontal directions.

5.2 Improvements

The platform where the vegetation was placed had stability problems especially at the end of the experiments were the plasterboard lost a lot of its structural capacity. This led to inaccurate results for the scale placed below. Thus, if the current setup is reused, the platform needs to be reinforced and stabilized to also mitigate the effect of the wind. Another solution would be to use a steel platform which would not deteriorate under the effect of the fire and be heavier to increase its stability.

Another improvement of the current setup would be to collect the firebrands leaving the tunnel. It appeared that some firebrands were leaving the test section, especially at higher velocities. However, these firebrands represent a portion of the total amount of firebrands produced and are important to perform a complete analysis. This could be done by placing the same type of thin mesh at the outlet of the tunnel. A water mist would prevent the firebrands from burning the mesh. More aluminium pans would be placed at the end of the test section, below the mesh, to collect the firebrands falling.

The possibility to differentiate cold and hot firebrands landing in the pans would also be a nice improvement to the current setup. To do that, a thin plastic film could be placed on top of each pan to detect the hot firebrands compared to the cold ones. The hot ones would melt through the plastic film and land directly on the mesh below where the cold ones would just stay on the plastic film or bounce on it. Another possibility would be to use a thermal gel that changes colour with high temperature.

One of the main limitations of the set up was the effect of the wind on the flame behaviour. During the preliminary tests it appeared that the flame started to tilt at around 1 m/s and that we couldn't reach a suitable flame engulfment of the trunks **(**Figs. 39 and 40) The flame being "flat" and close to the platform, it was not possible to ignite the top part of the trees where the branches were located for the experiments under 1 m/s and 2 m/s. The solution found was to reduce the area of the burner going from 60 cm by 30 cm to 30 cm by 30 cm. Reducing the area with the same propane flow gave us a higher flame height. However, this was not enough, and the problem persisted. Our final solution was to ignite the fuels using 0.4 m/s wind velocity and to change the wind velocity to 1 m/s or 2 m/s as soon as the ignition started.

A possibility to counteract this effect would be to increase the propane flow going inside the burner, thus increasing the HRR. However, this could damage the structure of the tunnel and especially the glass panels.

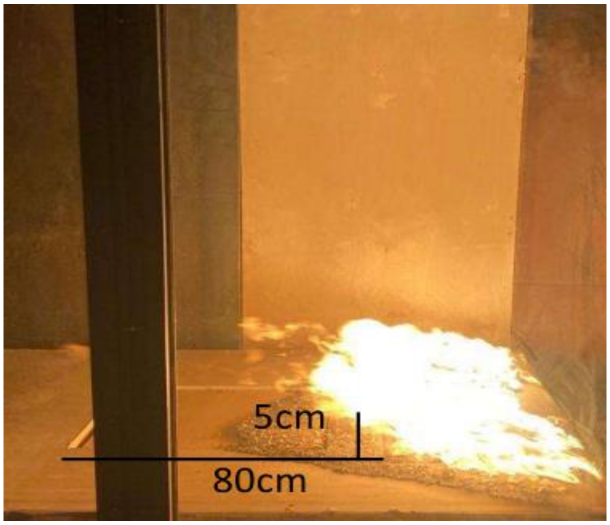

Fig. 39: Flame shape under 1 m/s wind

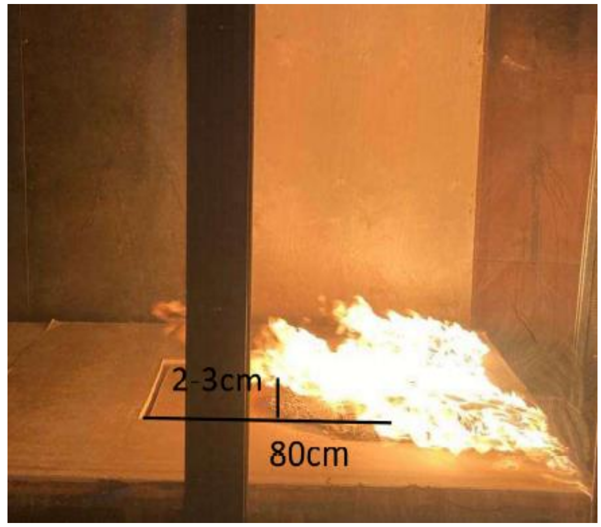

Fig. 40: Flame shape under 2 m/s wind

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Appendix A: MATLAB code used for the area distribution

```
============= [STEP 0] ==============================
%  Written by Matthew Nicastro
%  Based on code from James L Urban (Jurban@wpi.edu)
%
%  For Major Qualifying Project: Firebrand Generator (2021-2022)
%
%  no restrictions on use, adaptation, etc.
% ============================================

clear all
clc
close all


%%  [STEP 1] - Setup of Picture
% video file (INPUT)

% pic_file_path = 'C:\Firebrands\Branches\Exp1\';
pic_file_path = 'C:\Firebrands\Branches\Exp1\'; % Don't forget the "\" at the end!
% pic_file = 'BR1_7.jpg';
pic_file = 'BR1_7.jpg'; %input image name

i = imread(join([pic_file_path,pic_file]));

% INPUT: Reference Length-scale
Lx = 4; %cm

%%  [STEP 2] Determine pixel length of length-scale

% By default brighten factor should be 1
Brighten_factor = 1;

close all
figure; hold on
title("CLICK ON the top and bottom of the length-scale")
ref_points = round(readPoints(i*Brighten_factor,2))';
hold off

%%   [STEP 3] Determine the Size of the Firebrand

figure;
hold on
```

```
    im =     i(500:end-800,700:end-1500,:);  % Set Frame - Get rid of any black surfaces (don't cut
off the firebrand)
    % Cut off:(top, bottom, left, right)
    set(gcf, 'Units', 'Normalized', 'OuterPosition', [0 0 1 1]);

% Some black and white image processing magic
    frame_gray = im(:,:,3);
    threshold = graythresh(im);
    frame_bin = imbinarize(im(:,:,3), threshold);
    inv = imcomplement(frame_bin);

    imshow(inv(:,:)); hold on
    rp = regionprops(inv(:,:,1),'Area','BoundingBox');
    [~,idx]=sort([rp.Area]);  % Sort the regions by area - biggest is probably the firebrand
    rp=rp(idx);   % Actually sort them

    L = length(rp);
    n = 10; %INPUT: Number of firebrands to analyze
    for j = (L-(n-1)):L

    bb = vertcat(rp.BoundingBox);
    BB = bb(j,:);

    % Draw rectangular bounding box around firebrand
    rectangle('Position', [BB(1),BB(2),BB(3),BB(4)],'EdgeColor','r','LineWidth',2) ;
    % Confirm that the box is around only the firebrand
    j = j + 1;
    pause (.1); %shows the bounding boxes in steps, take this out or increase the delay if you want
    end
%%  [STEP 4] Calculate Firebrand Area

% Translate pixels to lengths
dx_pixels = max(ref_points(:,1)) - min(ref_points(:,1));
x_pixel_scale = Lx/dx_pixels;
k = 1;
for j = (L-(n-1)):L
% Calculate the area of the largest dark object in the frame (the firebrand)
    FB = rp(j,:);
    FBap = FB.Area;
    FBa = FBap*x_pixel_scale^2; % Area in cm^2

% Output the calculated firebrand area
disp ("The area of the firebrand " + k + " is: "+ FBa +"cm^2")
k = k+1;
j = j + 1;
end
```

Appendix B: MATLAB code used for the firebrand speed

```
%% ============================================
%  Written by James L Urban (Jurban@wpi.edu)
%
%  no restrictions on use, adaptation, etc.
% ============================================

clear all
clc
close all

%%
len_scale_video_file = 'Test3_Apr8';
v_len = VideoReader([len_scale_video_file '.mp4']);

% INPUT! ===============================
length_scale_frame = 200;
horiz_scale = 406.4;   % [mm]
vert_scale = 152.4;   % [mm]
% ====================================

%%

frame = read(v_len,length_scale_frame);
figure; hold on
title("Horizontal lengthscale - Click 2 points")
dx_pts = round(readPoints(frame,2))';
hold off

dx = abs(dx_pts(1,1) - dx_pts(2,1));
pix_2_mm_x = horiz_scale/dx;
%%

frame = read(v_len,length_scale_frame);
figure; hold on
title("Vertical lengthscale - Click 2 points")
dy_pts = round(readPoints(frame,2))';
hold off

dy = abs(dy_pts(1,2) - dy_pts(2,2));
pix_2_mm_y = vert_scale/dy;

%%
streak_video_file = 'Test3_Apr8';
v = VideoReader([streak_video_file '.mp4']);
```

```
%% Click!!!
figure('units','normalized','outerposition',[0 0 1 1]);
hold on

spark_array = [];

streak_data = struct();
% for n = 2:7

% INPUT! ==============================
start_frame = 250;
frame_skip = 3;
% ====================================

n = start_frame;
l = 1;
while 1
   frame = read(v,n);
   [new_streaks, flag] = readPointsSpark2(frame);
%     disp('================')
%     disp(new_streaks)
%     disp(size(new_streaks,2))
%     disp(size(new_streaks,2)>=2)


   if (flag == abs('q'))
      disp('Quitting!')
      break;
      disp
   elseif size(new_streaks,2)>=2
      streak_data(l).frame = n;
      streak_data(l).streak = new_streaks;
      streak_data(l).num_strks = size(spark_array,3);
      l = l + 1;

%         spark_array = cat(3, spark_array, new_sparks);
   end
   n = n + frame_skip;
end
disp('Done!')

close all

%%   Save the data
%%

save([streak_video_file '_strk_data.mat'], 'streak_data','pix_2_mm_y', 'pix_2_mm_y', '-mat')
```

****

```
% INPUT! ==============================
t_expo = 1./30.;
streak_video_file = 'Test4_15hz';    % NO file extension! (assumes mp4)
% ====================================
load([streak_video_file '_strk_data.mat'])   % Load the saved data

% Figure out how many streaks
total_num_sreaks = 0;
for l = 1:size(streak_data,2)
    total_num_sreaks = total_num_sreaks +  streak_data(l).num_strks;
end

v_streaks_total = zeros([total_num_sreaks, 1]);

cntr = 1;
for l = 1:size(streak_data,2)
    streak_data(l);
    v_strk = zeros(size(streak_data(l).streak,3));
    for j = 1:size(streak_data(l).streak,3)
        dx_pix = abs(streak_data(l).streak(1,1,j) -streak_data(l).streak(1,2,j));
        dy_pix = abs(streak_data(l).streak(2,1,j) -streak_data(l).streak(2,2,j));
        disp(dx_pix)
        dx_lab = dx_pix*pix_2_mm_x*1e-3;  % Convert to [m/s] from [mm] !
        dy_lab = dy_pix*pix_2_mm_y*1e-3;  % Convert to [m/s] from [mm] !

        dL = sqrt(dx_lab^2 + dy_lab^2);

        v_strk(j) = dL/t_expo;
        v_streaks_total(cntr) = dL/t_expo;
        cntr = cntr + 1;
%         break
    end
    streak_data(l).v_strk = v_strk;
%     break
end
save([streak_video_file '_strk_VEL_data.mat'], 'streak_data','v_streaks_total', '-mat')

disp("done")
% cat(streak_data(:).v_strk)

figure
histogram(v_streaks_total)
hold on
xlabel('firebrand speed [m/s]
```

Appendix C: Test protocol

Tree No:	Date:
Weight [kg]:	Time:
Moisture Content [%]:	Expected duration: 4 min of burning
Dimensions [mm] – Diameter: – Length:	

Preparation of the experiments

- Weight the tree
- Determine the average moisture content (4 measurements on the side, 5 on the diameter)
- Determine the dimensions of the tree (length and diameter)
- Take 4 pictures of the tree (each face)
- Place the tree on the platform

Test Procedure

Total time [s]	Test time [s]	Event
0	--	Start the mass recording
60		Start the Sony camera
120		Start the GoPro cameras
180		Start the fans
300	0	Ignition of the burner at 300 kW
--	--	Write any relevant observation and information about the test
540	240	Shut down the burner
600	300	Stop the Sony camera
660	360	Stop the GoPro camera
720	420	Stop the mass recording + Stop the fans

After the experiments

- Weight the burned tree
- Take 4 pictures of the tree (each face)
- Take out the pans from the test section
- Remove the meshes from the pans and place them into the drying box
- Dry the firebrands with the heater at 3000 W during 2 hours

Analysis of the firebrands

- Take pictures of the meshes to then characterize the firebrands using MATLAB (area)
- Use the side camera recording to determine the firebrand velocity using MATLAB
- Use the scale to weight the different meshes and determine the mass distribution