Experimental Study of Firebrand Lofting Mechanism in a Fire Whirl Induced Flow Field

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1 Abstract

This study aims to develop a new understanding of firebrands' lofting mechanism, which has taken the aerodynamic lift into account. A statistical approach of measuring the percentage of different paper lofting patterns has been introduced to evaluate the probabilistic behaviours of firebrand lofting. Samples of various aspect ratios and cross-sectional areas have been tested with and without the fire whirl. The experiment results have shown a noticeable increase in the percentage of the flying and floating samples with the existence of fire whirl. A simple analysis has shown that the aerodynamic lift should not be neglected. A quantitative analysis of the lift effect and drag effect has been introduced. In the calculation, the additional effect after introducing the aerodynamic lift fit the experimental results of fire whirl contribution.

2 Introduction

Spotting ignition caused by lofted firebrands is a significant mechanism of fire spread. And it tends to happen more occasionally on the larger scale of the main fire. A more significant fire will produce a greater and stronger plume with higher vertical and horizontal fire-induced wind velocity [1]. This fire-induced wind is capable of moving larger firebrands quite a long distance. Thus, researchers believed that firebrands could become the dominant fire-spread mechanism in large wildland fires [1] [4]. Moreover, following a growing body of evidence that firebrands are responsible for fire spread, understanding firebrand flight is necessary to explore the phenomenon of fire spotting.

Different investigations show that the current understanding of a typical process of firebrand spotting ignition is limited. Once a wildfire occurs, the combustion process affects the vegetative and woody structures, which generate the firebrands. Then, firebrands will be lofted up through the fire plume. Researchers believe that if the rise height is sufficient, the transporting mechanism converts from lofting to horizontal transporting [3]. However, in Tohidi's [2] research, the predicted result is quite sensitive to the coupling model, which indicated that the current understanding of firebrand is quite limited. Eventually, a spot fire may ignite upon landing on fuel far from the main fire area of the wildfire [4].

Many experimental studies have been undertaken since Manzello [5] developed the Fire dragon, a device to generate and release firebrands. Researchers studied the horizontals transportation and ignition after landing with the Fire Dragon. However, compared with the various experiment based on Fire Dragon, only limited experimental work has been conducted on the lofting mechanism of firebrands, especially under the fire whirl, which is assumed to be the main reason for the hyper-long distance spotting ignition.

In this word, a novel methodology to investigate the lofting mechanism is introduced. The factor of Affected Percentage is introduced to describe the possibility of a firebrand being lofted or fallen down directly. Using a two half-wall fire whirl generator setup, the impact of fire whirl on the firebrand lofting behaviour has been investigated. Eventually, a new hypothesis on the lofting mechanism was given to explain the phenomenon

3 Experiment Setup and Methodology

In this study, light paper pieces were used as samples for tests. They vary in size and aspect ratio. To minimise the effect of unstable burning, ethanol was introduced to replace the liquid fuel. An adjustable holder and iron ring were used to control the release of paper samples at the desired height. As shown in Figure 1(a), the height h is defined as the distance between the 5cm diameter fuel can's edge and the iron ring. In the experiment, 3cm, 5cm, 7cm, 9cm, and 12cm of release heights were carried out to investigate the fire whirl effect on the firebrand lofting. For the purpose of control variables, in the cases of testing the fire whirl's impact on the firebrand lofting, the size and aspect ratio of the paper samples were kept the same. In the experiment, paper samples of different aspect ratios (1:1, 1:2, and 1:3) have been tested. To make the cases more comparable, the cross-sectional area of all the paper samples were kept the same for these tests. The paper samples with different areas were also investigated separately. In total, there were two test groups and 18 cases, as shown in Table 1. The number of tests for each case was repeated at least 50 times.

Table 1. The cases of experiment.

Size of Paper Sample	*Released Height*
$1\text{cm} \times 1\text{cm}$	3 cm, 5cm, 7cm, 9cm, 12cm
$0.7\text{cm} \times 1.4\text{cm}$	7cm
$0.6\text{cm} \times 1.7\text{cm}$	7cm
$1\text{cm} \times 2\text{cm}$	7cm
$1\text{cm} \times 2\text{cm}$	7cm

This work is not focused on the study of fire whirl phenomena but rather its impact on the lofting mechanism of firebrands. Thus, a suitable setup for the fire whirl generator has been chosen, which is illustrated in Figure 1(b). Two transparent cylindrical walls, 30cm in height, 20cm in diameter, and 2mm in thickness, were arranged to generate the fire whirl. In order to prevent the thermal stress breakage as a result of uneven heating, acrylic walls were chosen. The gap between each half-cylinder wall controlled the intensity of the fire whirl. Two gaps of 0cm and 2cm were used. The 2cm gap led to a fire whirl generated in the hot flow, while the 0cm gap represented a control group of no whirl flow in this experiment.

A typical fire whirl generated by the half-cylinder wall has been demonstrated in Figure 2(a). For the group of 0cm gap, no fire whirl was generated. Therefore, the impact of fire whirl on the lofting mechanism could be investigated by comparing the behaviour of firebrands in these two groups.

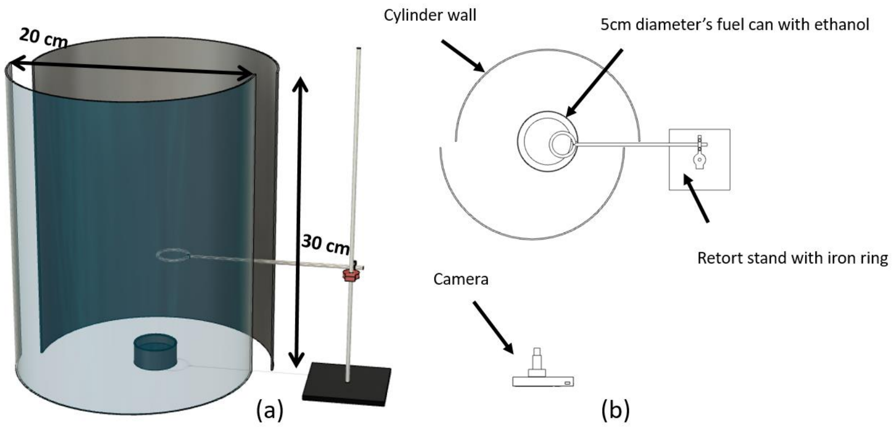
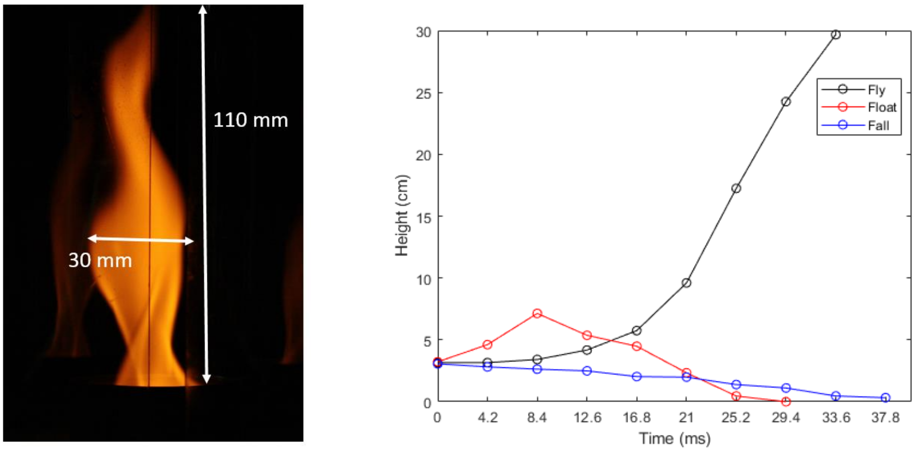


Figure 1 (a) 3D representation of the experimental setup (b) Top view of the setup

Figure 2 (b) shows the typical behaviour of each paper sample that was used to determine the impact of fire whirl on the lofting mechanism. The behaviours were classified into three types according to the outcome: flying, floating and falling. The flying paper samples and the floating paper samples indicated that it was being affected by the hot flow significantly. While, the falling group indicated that the paper sample did not show any height increase during the transport, which could be assumed as the neglected firebrands in reality.



(a) (b)

Figure 2. (a) A snapshot of the fire whirl generated by the experiment setup. (b) Lofting height versus time of the typical three firebrand's behaviours: fly up, float around and fall down directly.

4 Result and discussion

4.1 Effect of the Fire whirl to the firebrand's lofting mechanism

In order to control the shape effect of firebrands, the initial paper samples were cut into 1cm × 1cm squares. The Affected Percentage included both flying and floating groups, which could be the real long-distance transport firebrand that will ignite the surrounding fuels in reality. This suggests that the higher the percentage, the higher possibility of a spot fire occurring. Moreover, by analysing the tendency of the Affected Percentage while changing others variables, the relationship between these variables and spot fire was investigated.

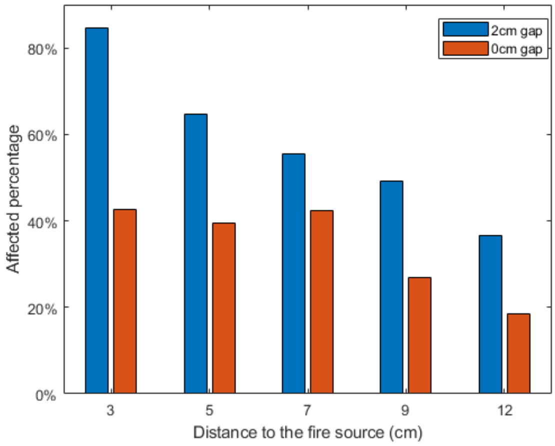


Figure 3. Affect percentage of firebrands lofted by the heat sources on different release heights.

As shown in Figure 3, when the release height is 3cm, 85% of the paper samples were affected by the fire whirl generator with a 2 cm gap. In contrast, when the 0 cm gap was applied to the Fire whirl generator (there is no fire whirl being generated), only 43% of the paper samples were affected. Thus, the fire whirl affected the behaviour of paper samples significantly. And this was also observed at different distances as well. For the release height of 5cm, the 0cm gap group only affected 40% of the whole released paper samples, while the 2cm gap group affected 65% of the samples. For the release height of 7cm, the 0cm gap group affected 42% of the samples, while the 2cm gap group affected 56% of the samples. In the 9cm distance to the heat source group, 49% of the samples were affected by the 2cm gap, while only 27% of the samples were affected by the 0cm gap. And by releasing the paper sample at a distance of 12cm, 37% of the samples were affected by the 2cm gap, while 19% of the samples were affected by the 0cm gap. The Affected Percentage of the fire whirl group is approximately two times higher than the non-fire whirl group.

4.2 Effect of the Fire whirl to firebrand's lofting mechanism for different shapes of firebrand

In this study, the release height was fixed in each group of experiments. The aspect ratio was varied to investigate the lofting mechanism of the fire whirl. In order to neglect the impact from irrelevant variables, in these experiments, all of the paper samples' cross-sectional area was to be 1 cm^2. And in this study, the tested aspect ratios were 1:1, 1:2, and 1:3.

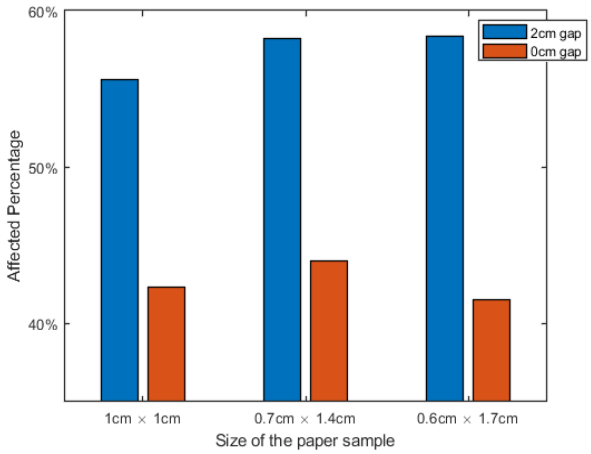


Figure 4. The affected percentage of three shapes (1*1, 0.7*1.4, and 0.6*1.7) when paper samples were released at 7cm height and lofted by 0cm gap and 2cm gap of the fire whirl generator.

As shown in Figure 4, the Affected Percentage was higher for those groups under the presence of the fire whirl in any aspect ratio. And for the tests of the aspect ratio of 1:2, 58% of the paper samples were affected in the 2cm gap group, while only 44% of the paper samples were affected in the 0cm gap group. For the test with the aspect ratio of 1:3, 59% of the paper samples were affected in the 2cm gap group, while only 42% of the paper samples were affected in the 0cm gap group. Moreover, along the increase of the aspect ratio the affected percentage tended to increase for the tests of 2cm gap, while 0cm gap group did not experience such phenomenon.

5 Analysis

As the experimental result indicated, the Affected Percentage for $1\text{cm} \times 1\text{cm}$ paper sample was increased by about 73.4% after introducing the fire whirl. It is clear that the tendency of moving upward for the paper sample in the fire whirl is much stronger than that without fire whirl. A stronger tendency of moving upward is usually equivalent to higher acceleration. Using Newton's second law, it is obvious that the net force of the firebrand with fire whirl should be larger than the other group. This phenomenon could be explained by analysing the aerodynamic forces. Then, it is essential to introduce the aerodynamic lift together with the aerodynamic drag.

$$F_l = \frac{1}{2} C_l \cdot \rho \cdot V_r^2 \cdot A_{ref}$$

where F_l is the aerodynamic lift. C_l is the lift coefficient, which is related to the firebrand's shape, angle of attack, and other flow conditions, V_r is the relative velocity of the firebrand to the surrounding flow, A_{ref} is the firebrand's reference area. The direction of the aerodynamic lift is perpendicular to the relative velocity. Compared with the aerodynamic drag:

$$F_d = \frac{1}{2} C_d \cdot \rho \cdot V_r^2 \cdot A_{ref}$$

where F_d is the aerodynamic drag. C_d is the drag coefficient, which depends on the shape of the object, angle of attack, and the Reynolds number of the system, V_r is the relative velocity of the firebrand to the surrounding flow, and A_{ref} is the firebrand's reference area. The drag is acting in the same direction of motion. In the above coefficients, the reference area A_{ref} is chosen to pertain to the given geometric body shape. For example, for a plane wing, A_{ref} is the planform area. And for a spherical object, A_{ref} is the cross-sectional area.

Decomposing the above equations into two sets of vector equations parallel to the x and y axes:

$$F_l = \underbrace{\frac{1}{2} C_l \cdot \rho \cdot \overrightarrow{V_{rx}}^2 \cdot A_{ref}}_{y\ direction's\ component} + \underbrace{\frac{1}{2} C_l \cdot \rho \cdot \overrightarrow{V_{ry}}^2 \cdot A_{ref}}_{x\ direction's\ component}$$

$$F_d = \underbrace{\frac{1}{2} C_d \cdot \rho \cdot \overrightarrow{V_{rx}}^2 \cdot A_{ref}}_{x\ direction's\ component} + \underbrace{\frac{1}{2} C_d \cdot \rho \cdot \overrightarrow{V_{ry}}^2 \cdot A_{ref}}_{y\ direction's\ component}$$

Where V_{rx} and V_{ry} are the x-axis and y-axis projections of the relative velocity of the firebrand to the surrounding flow.

In the experimental group that had no fire whirl, the flow velocity only consisted of the y-direction component. Thus, the aerodynamic lift is always horizontal to the up-lifting direction, and it does not affect the lofting. However, in the experiment group that included the effect of fire whirl, the aerodynamic lift effect varies significantly. Although the firebrands were stable, the surrounding flow direction was different. And this indicates the aerodynamic lift will not be perpendicular to the up-lifting direction all the time. Then the aerodynamic lift will affect the firebrand's lofting.

6 Conclusion

A systematic study was presented on the mechanism of firebrands lofted by fire whirl. This study included a comparison of firebrand lofting behaviour with and without fire whirl being introduced. Furthermore, a statistical method was introduced to quantify the differences in the behaviour of firebrands under different flow conditions,

The main conclusions are listed as follows:

- The fire whirl had a significant effect on the lofting mechanism of firebrands.
- The aerodynamic lift effect may be the reason for the significant effect of the fire whirl on the firebrand lofting.

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