Published in final edited form as:

Int J Heat Mass Transf. 2019 ; 130: . doi:10.1016/j.ijheatmasstransfer.2018.10.045.

Investigating Effect of Wind Speeds on Structural Firebrand Generation in Laboratory Scale Experiments

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Abstract

Firebrands generated from structures are known to be a source of rapid flame spread within communities in large outdoor fires, such as wildland-urban (WUI) fires, and urban fires. It is important to better understand firebrand generation mechanism to prevent structure ignitions by firebrands. Though the wind plays an important role during the large outdoor fires, little known is the influence of wind speeds on firebrand production. To this end, a series of experiments were performed using mock-ups of full-scale wall assemblies exposed to wind. The objective of this study was to examine if experiments with mock-ups of full-scale wall assemblies may provide insight into firebrand generation from structures. Specifically, generated firebrands were collected and compared with those collected from full-scale components and a full-scale structure. The relationship between projected area and mass of firebrands were compared with previous experimental data. It was found that the projected area of firebrands was proportional to the firebrand mass in this study, which is the same as those from experimental studies performed for full-scale components and a full-scale structure. The slope of the relationship of the projected area and the mass of firebrands was the same under the same wind speed and was affected by the applied wind speed within this experimental range.

Keywords

Firebrand; Generation; Large Outdoor Fires; WUI Fires; Urban Fires

1. Introduction

Large outdoor fires, such as urban fires, wildland-urban interface (WUI) fires and wildland fires/wildfires are an urgent problem across the world. WUI fires are frequently seen in the news, however oftentimes called wildfires mistakenly. WUI fires, which happen where communities and wildland vegetation coexist, have resulted in loss of life and property damage. In Europe, both Spain and Portugal have suffered large WUI fires, as well as California (USA) in 2017. Japan, whose cities are densely populated, has more of an urban

fire problem. These may or may not be produced after the occurrence of strong earthquakes. The recent 2016 Itoigawa City fire that occurred in Niigata, Japan, is an example where no earthquake was present, but a large-scale urban fire developed.

One of common features in both urban fires and WUI fires are structure ignitions [1]. While both urban fires and WUI fires are complex, it is possible to develop scientifically-based mitigation strategies by attempting to understand how structures are ignited in these fires. Post-fire disaster investigations have pointed to the significance of firebrands, or embers, as a leading driver for *both* fire spread and structure ignition [2-3].

Firebrand research may be divided into three important research areas, firebrand generation, firebrand transport, and ignitions by firebrands. Past research on firebrands have focused on firebrand transport, with little research conducted on firebrand generation and ignitions by firebrands [4]. Recent development of the firebrand generators and studies using those firebrand generators have advanced understanding of vulnerabilities of structures to firebrands significantly [5]. Nonetheless, far less progress has been made on understanding firebrand generation from structures. Understanding the characteristics of firebrands generated from structures will advance the understanding of firebrand transport and structure ignitions by firebrands.

Firebrand generation from structures was investigated both experimentally and during post-fire disaster investigations. In previous research on experimental firebrand generation, several actual structures were burned and firebrands were collected by polyurethane sheets [6, 7], along with other data. The size of firebrands was determined by measuring holes on those sheets and it was reported that the size of 85 % of firebrands captured by those sheets were less than 0.23 cm^2 . In another study, structure burns in wind tunnel facilities were performed and firebrands were collected by pans filled with/without water. Eighty-three percent of firebrands collected by pans filled with water were between 0.25 cm^2 to 1 cm^2 [8]. Firebrands collected after a three-story wooden school burn experiment reported the lengths of most of firebrands were between 1 cm to 3 cm. In post-fire investigation of an urban fire, firebrands were collected and also analyzed [9]. The projected areas of most of firebrands were smaller than 10 cm^2 with the mass of each firebrand less than 1 g. [9]. Past experiments have focused on investigating firebrand generation by burning entire structures. While it is realistic, conducting many full-scale experiments of structure firebrand production is costly and not easy to undertake. As a result, the authors have embarked on an experimental program to determine if smaller-scale experiments may produce useful insight into the firebrand production process.

First, an attempt to understand firebrand generation from an actual residential structure was made. During firefighting training with an actual residential structure, firebrands were collected with pans with water [10]. Second, an experimental burn under similar wind speed was performed with a simple structure made with Oriented Strand Board (OSB) and wood studs [11]. Firebrands collected from the simple structure had similar mass and size classes to those collected from the actual residential structure. Thirdly, a repeatable experimental method with full-scale wall assemblies were developed and showed possibility to predict

characteristics of firebrands from those experiments [12]. In addition, effect of sidings on wall assembly was investigated using the same methods [13].

The objective of this study is to investigate if experiments using mock-ups of full-scale wall assemblies may provide insight into firebrand generation from structures. Firebrands generated in the current work were collected and compared with those collected from previous experiments that made use of full-scale walls and a full-scale structure, constructed of common building materials [11-12]. The wind effect on firebrand production using a newly developed experimental method using mock-ups of full-scale wall assemblies was investigated.

2. Experimental Descriptions

A series of experiments with mock-ups of full-scale wall assemblies were performed in a wind facility in the National Research Institute of Fire and Disaster (NRIFD). NRIFD's wind facility has a 4 m diameter fan. The flow field was measured to be within $\pm 10\%$ over a cross-section of 2.0 m by 2.0 m. Experiments were performed within this cross-section.

Mock-ups used in this study were re-entrant corner wall assemblies, constructed with OSB and wood studs, with the dimensions of 0.6 m (W) $\times$ 1.2 m (H) (Fig. 1), which are the same materials used in previous experiments. The mock-up assembly is half the height and width of the full-scale corner wall assemblies used in previous experiments. The comparison is shown in Fig. 2 [12].

Experiments were performed in the following manner. Mock-up assemblies were ignited by a T-shaped burner with heat release rate (HRR) of $32 \text{ kW} \pm 10\%$ for 5 minutes. The reason to ignite under no wind was to provide consistent flame contact area for the assembly ignition for all experimental cases, independent of the wind speed. These afforded repeatable ignition conditions.

Important lessons learned from the full-scale wall assembly experiments were applied to develop the ignition methodology for the mock-up assemblies. The ignition time used for the mock-up assemblies was half of that used for the full-scale assemblies (5 min vs. 10 min for the full-scale assemblies; for T-shaped burner HRR the same within experimental uncertainty). The total ignition time of 5 min was very important and carefully selected during ignition under no wind using a trial and error procedure. If an ignition time less than 5 min was applied, once the wind field was added, the wall assembly would self-extinguish, and little or no firebrand collection was possible due to lack of combustion. If an ignition time longer than 5 min was applied, the wall assembly was observed to be consumed a great deal before the application of wind, thus rendering it unstable for firebrand collection (i.e. large holes were formed due to long ignition combustion process compromising the structural integrity).

After the burner was turned off, desired wind speed (4 m/s, 6 m/s or 8 m/s) was applied. Experiments were stopped when the combustion of the assemblies was completed or the assemblies were not able to support themselves anymore.

A series of pans filled with water, placed downwind from the assemblies, were used to collect firebrands generated from the mock-ups. Water was needed to quench combustion otherwise only ash remained when experiments were finished. After the experiments, pans were collected, and firebrands were filtered and dried at 104 °C for 24 h. Dried firebrands were measured with a scale and pictures were taken for image analysis, shown in Fig. 3

3. Results and Discussions

Fig. 4 displays an image of an experiment with a mock-up of the corner wall assembly under an 8 m/s wind. After each experiment, firebrands were collected and analyzed. To investigate the effect of winds on characteristics of firebrand generation, the projected area and mass was plotted. While most of firebrands did not have constant thickness, the relationship between the projected area and mass can be described as follows;

$$m_{firebrand} = \rho_{firebrand} \times t_{ave, firebrand} \times PA_{firebrand} \quad (1)$$

Here $m_{firebrand}$ is the firebrand mass, $\rho_{firebrand}$ is the firebrand density, $t_{ave, firebrand}$ is the firebrand average thickness perpendicular to the projected area, and $PA_{firebrand}$ is the firebrand projected area. In this study, the mass and the projected area of firebrands were measured. Thus, firebrand data under each condition were also examined to be fitted into linear equations in the form of Eq 1.

3.1 Repeatability

First, experiments with mock-ups of the full-scale wall assembly were conducted to investigate the repeatability of firebrands produced with the methodology developed in this study. Figure 5 shows the projected area and the mass of firebrands in two experiments under a 6 m/s wind condition. The relationship between the projected area and the mass looks quite similar as shown in Fig. 5 with more than 200 firebrands analyzed from each experiment. The value of slope shown in Fig. 5 was can be considered the same for both cases (within uncertainties). As it is proven that the relationship between the projected area and the mass of firebrands was similar, a histogram of the projected area is provided as Figure 6. Figure 6 shows that firebrands with less than 0.90 cm² projected area is dominant, while still relatively large firebrands, which have more than 14.44 cm² projected area, were found. It is shown the ratio of size band of firebrands produced in this study is also similar.

3.2 Comparison with the full-scale corner wall assemblies and the full-scale structure

Fig. 7 (a) and (b) shows the comparison of the projected area and mass of firebrands generated from both mock-up and full-scale corner wall assemblies [12] under two different wind speeds, 6 m/s and 8 m/s, respectively, as well as from a full-scale structure burning [11] under 6 m/s wind speed. While some of firebrands were more than 1 g, more than 90 % of firebrands collected in this study were relatively small with less than 1 g mass and 10 cm² projected area. This was similar to firebrands generated from the full-scale wall assemblies [12] and the full-scale structure [11]. While ignition methods for corner wall assemblies were similar both at full-scale and laboratory experiments, with the similar T-shaped burner

applied for a certain duration, the ignition method for the full-scale structure was different as a sofa was used to produce flashover to ignite from the inside. The similarity of firebrands generated with different ignition methods is an interesting finding.

Fig. 8 (a) and (b) provides a histogram to better show the various firebrand sizes grouped in distinct size classes. The comparison of firebrands generated from mock-ups and full-scale corner wall assemblies [12], as well as a full-scale structure [11] showed firebrands with similar size classes might be observed. The main difference was that the mock-up assemblies had more firebrands less than 0.9 cm^2 in projected area than those from the full-scale wall assemblies for both wind speeds. Yet, it was shown that firebrands had larger projected area as the wind speed increased for both mock-ups and the full-scale wall assemblies.

Of equal importance was that the mock-up wall assemblies produced firebrands across the same four size classes to those from the full-scale wall assemblies (see Fig 8 (a) and (b)). Even though the total percentages varied across each size class, this is not important. Rather, this information suggests that mock-ups wall assemblies may be used to assess key firebrand production characteristics needed for firebrand transport calculations as well as structure ignition research by firebrands (i.e. what range of sizes should be used for firebrand generator experimentation).

3.3 Wind effect on firebrand production

Figure 9 shows the projected area and mass of firebrands under three wind speeds, namely 4 m/s, 6 m/s and 8 m/s. As it was discussed above (see (equation 1)), the projected area and the mass of firebrands have a liner relationship. However, it is shown that the value of slope varies with the wind speeds. Thus, Figure 10 is shown the relationship between the wind speed and the value of slope. The uncertainties of the values of slope are standard deviations in Figure 10. As shown in Figure 10, it was observed that the value of the slope increased as the wind speed increased from 4 m/s, 6 m/s to 8 m/s. As it was assumed the density of OSB at the moment of breakage was constant, the difference in the slope of the graph was affected by the firebrand average thickness at the time of breakage.

For firebrand generation mechanisms from structures, wind force plays an important role, as the force is dependent on the applied wind speed:

$$F_{wind} \propto v^2 \quad (2)$$

Here F_{wind} is the wind force applied to the assemblies and v is the wind speed. Clearly, F_{wind} would influence the breakage of firebrands from the assembly. Firebrands are generated as the combustion on the assembly progresses. The data in this study suggest that higher wind speed results in thicker firebrands being produced as the wind speed was increased. While there are no fundamental studies of firebrand breakage dynamics from structural fuels (used here), there are some investigation for these mechanisms from vegetative fuels, such as trees [14, 15]. These important measurements in the present paper will motivate similar investigations on firebrand breakage dynamics for structural fuels.

4. Summary

A series of experiments were performed to investigate if experiments with much simpler mock-ups may provide the insight of firebrand generation from structures. The comparison of firebrands generated from mock-ups, and full-scale corner wall assemblies, and a full-scale structure, showed firebrands with similar size and mass classes may be observed. These findings suggest that mock-ups wall assemblies may be used to assess key firebrand production characteristics needed for firebrand transport calculations as well as structure ignition research by firebrands (i.e. what range of sizes should be used for firebrand generator experimentation). This approach is to attempt to develop test methods to screen building materials for firebrand production. In this manner, it may be possible to design structures that produce a reduced number of firebrands.

The relationship between projected area and mass of firebrands were compared with previous experimental data. It was found that the projected area of firebrands was proportional to the firebrand mass in this study, which is the same as those from the full-scale components and the full-scale structure experiments. The slope of the relationship of the projected area and the mass of firebrands was the same under the same wind speed and was affected by the applied wind speed within this experimental range. Those data would be beneficial for future computational studies to simulate firebrand behaviors under wind. While these results are encouraging, significantly more work is needed to determine if such simple experiments may capture more complex firebrand production effects, such as the addition of siding materials.

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Figure 1.
Schematic of mock-ups of full-scale corner wall assemblies.

Figure 2. Comparison of the size of mock-ups of the full-scale wall assembly used in this study (left) and the full-scale wall assembly in previous study [12] (right).

Figure 3.
Images of firebrands generated from mock-ups under 6 m/s (top) and 8 m/s (bottom) wind.

Figure 4. Image of an experiment under 8 m/s wind. Mock-ups used in this study were corner wall assemblies, constructed with OSB and wood studs with the dimensions of 0.6 m (W) $\times$ 1.2 m (H).

Figure 5.
Comparison of two experiments under a 6 m/s wind.

Figure 6.
Comparison of size of firebrands from two experiments under a 6 m/s wind.

(a)

(b)

Figure 7. Comparison of the projected area and the mass of firebrands generated in this study to those in previous studies [11, 12] under (a) 6 m/s (top) and (b) 8 m/s (bottom).

(a)

(b)

Figure 8.

Comparison of the size distribution for mock-ups to the full-scale corner wall assembly and full-scale structure [11, 12] under (a) 6 m/s (top) and (b) 8 m/s (bottom).

Figure 9.
Comparison under different wind speeds.

Figure 10.
Effect of wind speeds on characteristics of firebrands.