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Characteristics of Firebrands Collected from Actual Urban Fires

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Abstract. The characteristics of firebrands collected from a recent urban fire in Japan are described. Specifically, this fire broke out from a Chinese restaurant in Itoigawa-city, Niigata, Japan on December 22nd 2016. On the day of the fire, strong winds resulted in rapid fire spread. With the presence of an average wind speed of 9 m/s, the fire quickly spread, resulting in the damage of 147 structures, with 120 of 147 destroyed. The fire was extinguished more than 30 h later. During the fire, firebrands were observed and 10 spot fires were reported. After the fire, investigations were performed and firebrands were collected from the burn site. The size and the mass of firebrands were measured and compared with the available literature data. It was observed that more than 60% of the collected firebrands had less than 0.10 g mass and 2.0 cm^2 projected area and the size and the mass of firebrands were independent of the location. The size and the mass of firebrands from this fire were similar to those from another urban fire under similar wind speed and were also compared to those produced from a firebrand generator. The firebrand data set presented here provided valuable insights into how firebrands are generated from structures in actual urban fires. Finally, the description on how a firebrand generator may be used to produce firebrands similar to urban fires yields an important advancement to begin to study such complex phenomena in the laboratory.

Keywords: Urban fire, Firebrands, Spot fires, Post-fire investigation, Large outdoor fires, Embers

1. Introduction

Firebrands are known to be an important mechanism in large outdoor fire spread, such as Wildland-Urban Interface (WUI) fires and urban fires. Post-fire disaster investigations show that firebrands are a cause of rapid fire spread [1, 2]. Research on firebrands has focused on transport for many years [3–6], with only recent attention directed on understanding how firebrands may ignite structures [7]. A very limited number of studies have investigated firebrand generation from structures in large outdoor fires [8–12], and more data of characteristics of structural firebrands is needed from actual fires.

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Few investigations related to firebrand production from urban fires have been performed to date [8–10]. Spot fires were reported from a hotel fire in Wakayama, Japan in 1998 [8]. Interviews with residents were conducted and the maximum length of firebrands observed in this fire was found to be 5 cm. In another urban fire in Beppu-city, Oita, Japan in 2010, the wind speed on the day of the fire was around 10 m/s. Shinohara et al. [9] collected firebrands on site after the fire and conducted interviews with residents. Most of the firebrands collected had mass less than 0.5 g and projected area less than 10 cm^2. Suzuki [10] performed three different fire investigations for firebrand production from structures. Those fires did not cause spot fires due to firefighting efforts. Even without spot fires, the characteristics of firebrands were similar to those collected from other post-fire investigations. In addition, Manzello and Foote [11] investigated the size of firebrands in WUI fires by examining the burn patterns generated by the firebrands landing on the trampolines and the same method was applied to Bastrop Complex fires [12]. Both of these WUI fire studies found that the majority of firebrands were of projected areas of less than 1.0 cm^2.

Several *experimental* studies on firebrand generation from structures have been performed [13–22]. Vodvarka investigated firebrand generation by igniting 5 full-scale residential houses [13] and later 8 full-scale residential houses [14]. Both experimental series were performed outside and firebrands were collected by polyurethane plastic sheets. Residential houses used in the experiments were made of different materials. It was concluded that small size firebrands were dominant, especially those with projected area of less than 0.23 cm^2.

Yoshioka et al. [15] conducted structure burn experiments using the wind tunnel at the Building Research Institute (BRI). Firebrands were collected by using a pan with water (labeled as wet pans) and a pan without water (labeled as dry pans) placed downwind from a structure constructed from fire wood with siding and slate roofing. The number of firebrands collected in the dry pan was smaller than the number of those in the wet pan. It was also found that in terms of the average size of firebrands collected in this study, the ones in the dry pan was larger than the one in the wet pan.

Suzuki et al. [16–19] conducted a series of experiments on firebrand generation from structures. In the first study, a residential house, in Dixon, California, USA was burned for fire fighter training [16]. Firebrand collection was performed during the burn to investigate characteristics of firebrands from an actual residential house. Firebrands were collected by pans filled with water. In the second study, a structure made from simple oriented strand board (OSB) and wood studs was ignited in BRI's wind tunnel and firebrands from the structure were collected and characterized [17]. In the final of the three studies, simple assemblies (walls) of building components made from OSB and wood studs were ignited to examine if simple components experiments may provide insights into actual structure burns [18]. It was indeed confirmed by these components experiments that the characteristics of firebrands from building components were similar to those from an actual residential house. The same experimental method was used to investigate the effect of siding on firebrand generation [19]. These data have been used for the NIST firebrand generator to produce firebrands which correspond to those from structures [20].

In other studies, a three-story-wooden school was burned, and firebrands, along with other data, were collected [21, 22]. Firebrand collection was performed for a 3-month period after the burn was finished. It was reported that the length of most of firebrands were between 1 cm and 3 cm. All the salient information on the fore mentioned studies is summarized in Table 1.

In the past, information from residents suggested the existence of copious firebrand generation in Japan, such as that reported in the Sakata fires [2]. Due to the effectiveness of the evacuation for the Itoigawa fire, unlike previous large urban fires [2], there were few eyewitness accounts of this fire.

To this end, characteristics of firebrands from the Itoigawa-city fire was investigated and compared with existing firebrand data.

1.1. About the Fire

A fire broke out from a Chinese restaurant in Itoigawa-city, Niigata, Japan, around 10:20 am on December 22nd 2016. One hundred and forty seven (147) structures were damaged by the fire, with 120 of 147 destroyed. It was a windy day with an average wind speed of 9 m/s and gusts up to 27 m/s were reported [23]. The fire was extinguished by 4:30 pm on December 23rd 2016, some 30 h after the fire started. Almost 100 firefighters, including volunteer firefighters, were working on this fire [24]. Firebrands were lofted over a large area and ignited around 10 structures [24], which caused fires to propagate quicker than anticipated and overwhelmed the firefighters.

The first spot fire was reported before 11:20 am, only one hour after the fire initiated. Soon another spot fire followed. The burned area was approximately 40,000 m^2. The burned area and the locations of the spot fires are shown in Fig. 1. The structures which were ignited by firebrands were wooden structures with Japanese style tile roofing assemblies. In this fire, initially two hundred and seventy three (273) households were ordered to evacuate around 12:30 pm. Subsequently, another 90 households were then ordered to evacuate around 4:30 pm, for a grand total of 363 households placed under evacuation orders [24]. Figure 2 shows an image of a structure which received a spot fire on the roof. This fire is now considered the worst urban fire in Japan in the last 40 years, after the Sakata Fire [25].

1.2. Firebrand Collection

Firebrands were collected at various locations in the city (in the burned area) during the post-fire investigation as shown in Fig. 3. In total, 277 firebrands were collected and the one shown in Fig. 4 was later provided by the Itoigawa-city Fire Department. Collection locations were carefully selected to sample firebrands from the fire and from locations close to known spot fires. For example, the rooftops of tall structures were selected as collection points, since firebrands could arrive there only by flying. Nevertheless, it is impossible to collect all the firebrands generated from this fire. Other collection locations within the burned area included one resi-

Table 1
Summary of Firebrands from Structures and Urban/WUI Fires

	Material used	Wind speed	Measurement techniques	Significant results
Ohmiya and Iwami [8]	Not mentioned	An average 7 m/s	Survey	Most of the firebrands less than 5 cm maximum dimension
Shinohara et al. [9]	Not mentioned	An average wind speed of 7.2–12.1 m/s, with the maximum wind speed 20.1 m/s	Collected after fire	Most of firebrands less than 10 cm^2 and 0.5 g
Suzuki [10]	One of structures is made from wood frame and stucco wall	Less than 3 m/s	Collected after fires	Most of firebrands less than 5 cm^2 and 0.2 g
Manzello and Foote [11]	Not specified	4.5 m/s to 6.7 m/s (sustained) gusts to 13 m/s	Trampoline outdoor furniture	More than 95% of firebrands less than 1.0 cm^2
Rissel and Ridenour [12]	Not specified	5.4 m/s to 6.3 m/s (sustained) gusts to 13 m/s	Trampolines	More than 90% of firebrands less than 0.5 cm^2
Vodvarka [13]	Standard frame construction with wood siding /asphalt siding applied over sheet rock / brick veneer over a wood frame	Not specified	Sheets of polyurethane plastic	89% of firebrands less than 0.23 cm^2
Vodvarka [14]	All wood construction /cement-block construction with Wooden floors and asphalt shingles over wood sheathing	Not specified	Sheets of polyurethane plastic	85% of firebrands less than 0.23 cm^2
Yoshioka et al. [15]	Fire prevented wood with outer wall siding and slate roofing	4 m/s	Pan filled with water and no water	83% of firebrands in the wet pan between 0.25 and 1 cm^2
Structure burn in CA [16]	Wood and brick	6 m/s	Pans filled with water	All the firebrands less than 1 g Most of the firebrands less than 10 cm^2
Full-scale burn in wind tunnel [17]	OSB and wood 2 × 4 studs	6 m/s	Pans filled with water	More than 90% of firebrands were less than 1 g

Table 1
continued

	Material used	Wind speed	Measurement techniques	Significant results
				More than 90% of the firebrands less than 10 cm^2
Components [18]	OSB and wood 2 × 4 studs	6 m/s	Pans filled with water	More than 90% of firebrands were less than 1 g
		8 m/s		More than 90% of the firebrands less than 10 cm^2
Components with sidings [19]	OSB and wood 2 × 4 studs with cedar shingles sidings applied	6 m/s	Pans filled with water	67% (6 m/s) and 90% (8 m/s) of firebrands were less than 1 g
		8 m/s		75% (6 m/s) and 97% (8 m/s) of the firebrands less than 10 cm^2
3 story school building burn [21, 22]	Wood and gypsum boards	4.6 m/s	Collected after fire	Most firebrands were found to be between 1 and 3 cm

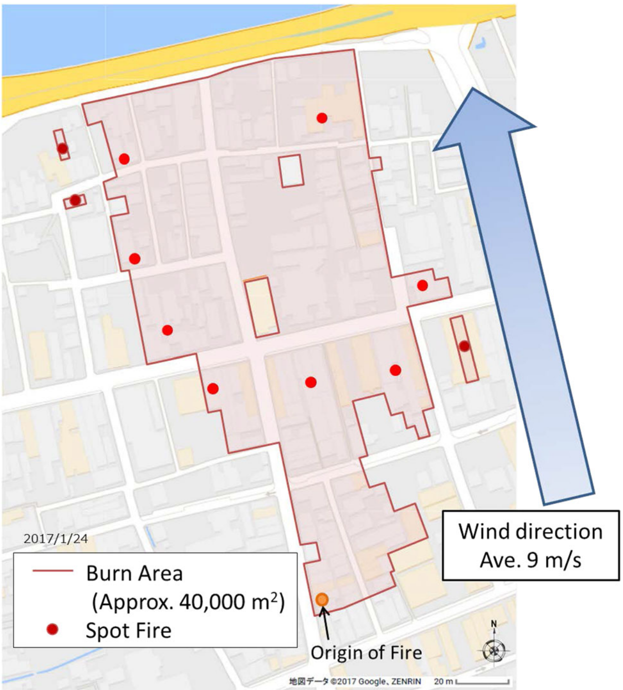

Figure 1. The map of the burned area and the locations of spot fires.

Figure 2. One of structures which survived after the ignition on roof This ignition is considered to be caused by firebrands.

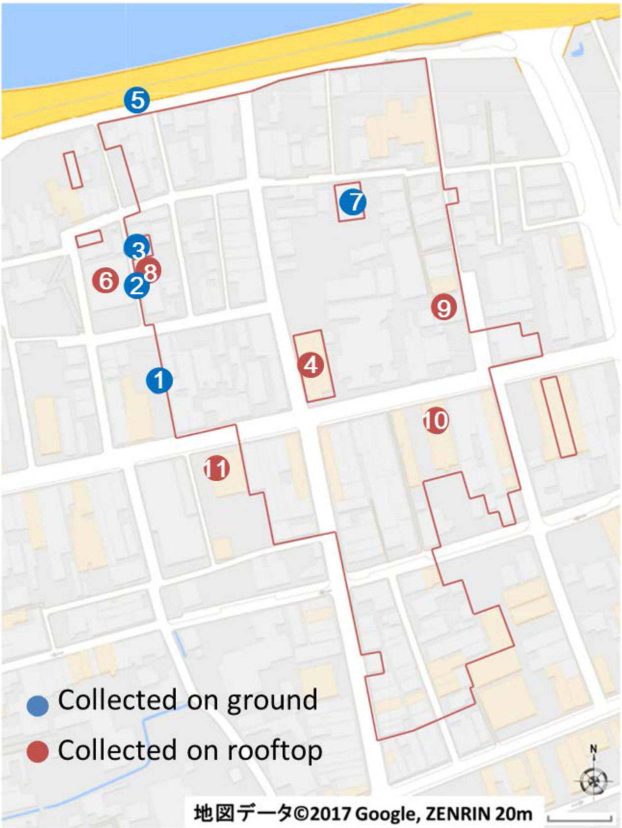

Figure 3. Locations of firebrand collection during the investigation.

Figure 4. Biggest firebrands found in this fire found on the building 9 (the firebrand was provided by Itoigawa-city Fire Department).

dential house which survived this fire. The house had adapted more fire-resistant construction techniques and faced a parking lot on two sides and a road on one side, and was next to the large backyard of a neighborhood Japanese sake brewery. It was reported that volunteer firefighters worked quite hard on this house as the owner himself is a volunteer firefighter. Most of firebrands were found partly wet due to the weather, as it rained after the fire, and was raining during the investigation. Most of the firebrands were collected by investigation teams with the help of residents. One of the firebrands was collected by a local fire department during their investigation and later provided to NRIFD (Fig. 4). This large size firebrand was found on the rooftop of a 4-story building (location 9 in Fig. 3).

After the collection, firebrands were oven-dried at 104° for at least for 48 h, until the mass of firebrands became constant before the measurement. Each firebrand was weighed using a scale with a resolution of 0.0001 g and then photographed to measure the maximum projected area. Image analysis software was used to determine the projected area of a firebrand by converting the pixel area using an appropriate scale factor. It was assumed that deposited firebrands would rest flat on the ground and the projected areas with the maximum dimension and the second maximum dimension of three dimensions were measured. Images of well-defined shapes (e.g. circular objects) were used to determine the ability of the image analysis method to calculate the projected area. Based on repeat measurements of different areas, the standard uncertainty in determining the projected area was 10%. Figure 5 shows some of pictures of firebrands collected in this fire.

2. Results and Discussion

Figure 6 shows the distributions of the size and the mass of all firebrands collected. While the biggest firebrand collected in this fire, shown in Fig. 4, had a mass of 114 g and a projected area of 130 cm^2, with 3 cm thickness, more than 60% of the collected firebrands had less than 0.10 g mass and 2.0 cm^2 projected area. Figure 6 shows the size and the mass of firebrands were independent of the location; either on the rooftop or on the ground. As mentioned, the biggest firebrand in this fire was found on the rooftop of a 4-story building (location 9 in Fig. 3).

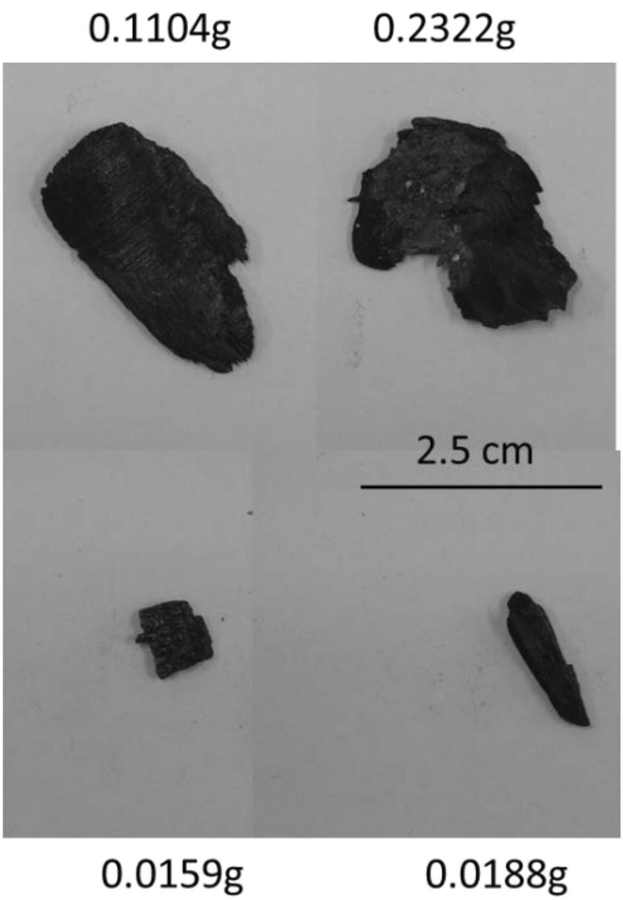

Figure 5. Images of firebrands collected in this fire.

The Tachikawa number, or the ratio of aerodynamic forces to gravitational forces, is used to characterize wind-brown debris [26]. The Tachikawa number (Ta) is defined as:

$$\mathrm{Ta} = \frac{\rho_{air} U^2 \mathrm{A}}{2 m_{firebrand}\, g}$$

Here ρ_{air} is the density of air, U is wind speed, $m_{firebrand}$ is mass of a firebrand, and A is projected area of a firebrand. The larger the Tachikawa number is, the further the debris can fly. This relationship was investigated in past studies [9, 22], and the conclusions were somewhat different. Post-fire investigations [9] showed little relationship while large building fire experiments [22] showed a relationship. In [9], it is important to keep in mind that the source of firebrands was assumed to be the same as the origin of the fire, which might not be accurate. The authors

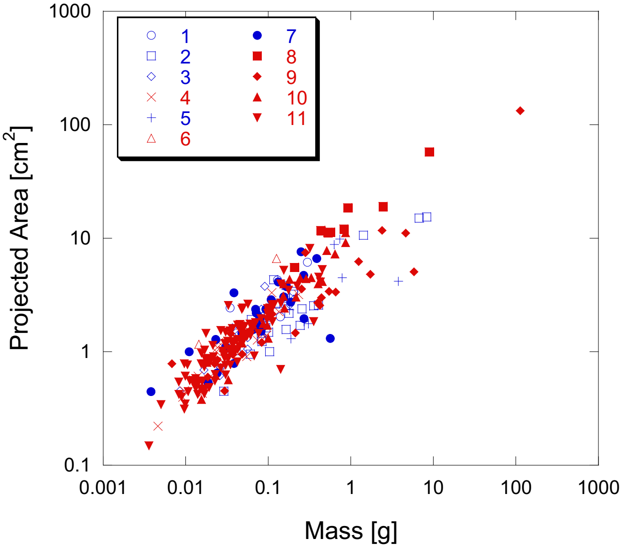

Figure 6. Distributions of the size and the mass of all firebrands collected in this fire. Red and blue referring to Fig. 3.

mentioned difficulty in locating an accurate source of firebrands [9]. Assuming all the collected firebrands were produced from the origin of the fire, Fig. 7 shows the relationship between $A/m_{firebrand}$ (as Ta $\propto \frac{A}{m_{firebrand}}$) and the distance from the origin of the fire. Figure 7 shows no relationship between the two, which means the assumption that all the collected firebrands were generated from the origin of the fire was not the case. This shows the difficulty in locating the actual source of the firebrands in the investigations.

It is important to compare the previously obtained firebrand data with the existing investigation data. Unfortunately, there were no data from any actual fire which completely matches the condition. Figure 8 shows the comparison of firebrands in this fire with the existing investigation data. The wind speed during this fire in Beppu-city was (7.2–12.1) m/s, which is close to the wind speed during the Itoigawa-city fire [9]. In the Beppu-city fire, residents found the ignition at the corner of a balcony caused by firebrands and extinguished. Out of 23 firebrands collected in their investigation, only 1 had a mass bigger than 1 g and a projected area larger than 10 cm^2. Figure 8 shows firebrands from both fires have similar mass and size classes.

Figure 9 shows the comparison of the firebrands from this fire with the firebrand data from the NIST firebrand generator. Details of the NIST firebrand generator are provided elsewhere [7]. Currently this technology is used to investigate structure ignition by firebrands as well as firebrand transport. The current version of the NIST firebrand generator has the capability to produce continuous firebrand showers, commensurate to those with firebrand data from structures under 6 and 8 m/s wind conditions [20].

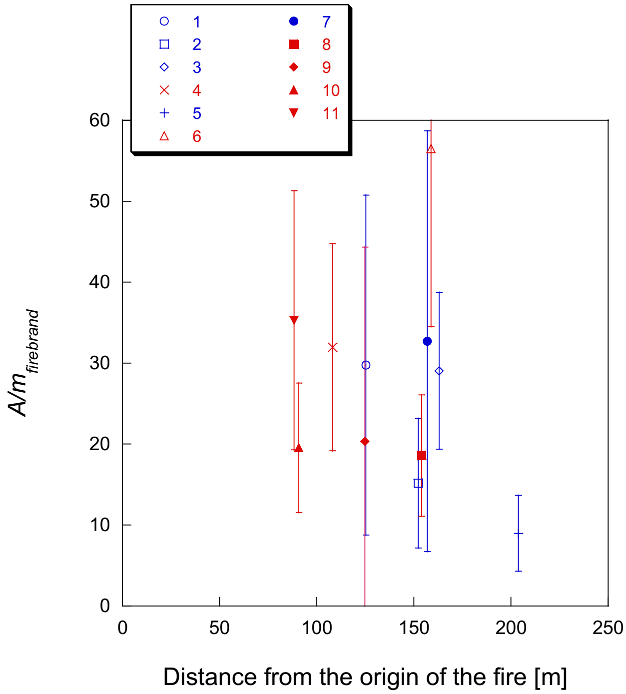

Figure 7. Relationship between mass per unit area and location. Mass per unit is supposed to be related to traveling distance of firebrands.

A firebrand generator experiment inside BRI's wind tunnel was performed under 9 m/s, which is close to the average wind conditions in the Itoigawa-city fire. Firebrands were collected by arrays of pans filled with water. Then firebrands were dried and analyzed in the same manner as this post-fire investigation. Figure 9 shows that the relationship of the size and the mass of most of the firebrands in both cases produced similarities for mass classes up to 0.2 g. The Itoigawa-city fire produced firebrands with masses larger than 0.2 g. While the collection method used to sample the firebrands from the NIST firebrand generator was different from that used in the investigation (water pans), the salient results of this comparison indicate that it is possible to produce firebrands using unique laboratory firebrand generators in the range of size and mass classes collected from actual large outdoor fires. While the number and mass *flux* of actual large outdoor firebrand generation remains elusive, the firebrand generator technology allows these parameters to be varied to ascertain the influence of firebrand flux on ignition propensity of structural fuel elements. As data is collected from actual fires, it desired that these firebrand generators be tuned to reproduce actual firebrand fluxes.

In this study, attempts are made to bring quantification of firebrand production from actual large outdoor fires. While there have been many post-fire studies con-

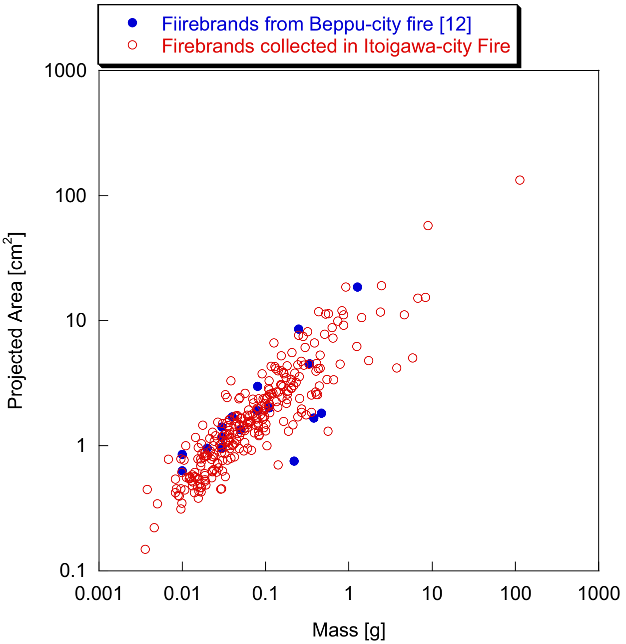

Figure 8. Comparison of size and mass of firebrands with Beppu-city fire and Itoigawa-city fire.

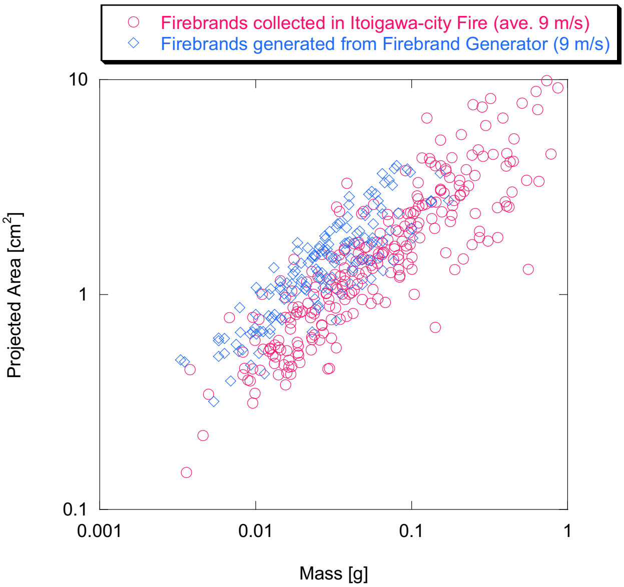

Figure 9. Comparison of size of mass of firebrands produced from firebrand generator.

ducted, these have not quantified any information about firebrand sizing [1, 2]. While it was not possible to collect all the firebrands from an actual fire, the careful analysis techniques presented here may serve as a basis for future quantification from actual fires. While it is often mentioned in countless literature studies that firebrands are a major issue in large outdoor fires, the current lack of quantification from actual fires greatly hampers a better understanding of this problem. The authors strongly desire that the methodologies discussed here will be useful to future post-fire investigations.

3. Conclusion

The characteristics of firebrands collected in an actual urban fire in Itoigawa-city, Niigata on 22nd December 2016 was investigated. It was found that more than 60% of the collected firebrands had less than 0.10 g mass and 2.0 cm^2 projected area and the size and the mass of firebrands were independent of the location. Firebrand data was compared with the existing data sets in the literature. The urban firebrand data set presented here was also found to be similar to those generated from a firebrand generator (up to 0.2 g) under similar wind speed as the actual fire. While more firebrand data is certainly needed from actual fires, this firebrand data from an urban fire, in which 147 structures were damaged, with 120 of 147 destroyed, provided insights into how firebrands generated from structures in urban fires are produced.

Little firebrand data from actual WUI fires are available at the current moment [11]. While firebrands in WUI and in urban fires are generated from structures, there is not enough data to ascertain important conclusions about potential similarities or differences of the generated firebrands between these fires. The data set present here, from an actual urban fire, is an important step in this process. Moreover, the description on how a firebrand generator may be used to produce firebrands similar to urban fires yields an important advancement to begin to study such complex phenomena the laboratory.

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