Research paper

Investigation on liquid atomization mechanism in Japanese sparkler “Senko-hanabi”

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Abstract

Sparkling firework, which is a Japanese sparker called Senko-hanabi, is composed of black powder containing no metal wrapped in a twisted paper. The firework has a unique beauty with streaks of light similar to the pine needles. For over 300 years, however, physics behind the beauty of the firework is hidden mystery. In this study, detailed high-speed visualization measurements are conducted to quantify the individual stages in the life of sparkling firework. It is confirmed that the droplets, which will be the streaks of light, are formed from liquid atomization induced by bursting of the fireball itself or the bubbles on the surface. The rupture process of non-evaporative droplets is successfully captured, and it is determined that the bursting of a droplet is caused by microexplosion, which is the sudden expansion of gas produced inside the droplet.

Keywords : fireworks, senko-hanabi, high-speed video, visualization, liquid atomization, bursting bubble

1. Introduction

Fireworks have long been popular all over the world. People are naturally attracted to a spectacular fireworks display in the night sky. A single large firework can spread a colorful display to a diameter of several hundred meters. The bright colors are produced by flame reactions of metal compounds. There are also small fireworks that can be safely held in the hand or fixed to a birthday cake. Since the Edo period over 300 years ago, one of the hand held types, sparkling fireworks, have been popular in Japan called *Senko-hanabi*. Sparkling fireworks are composed of black powder, which is a mixture of potassium nitrate (60 wt%), soot and/or charcoal (15 wt%), and sulfur (25 wt%), simply wrapped in a twisted paper that is approximately 20 cm long. They do not contain metal powders and the temperature of light streaks is relatively low at 1000 K. Their streaks of light become luminous mainly by black body radiation and not by a flame reaction. As the result, sparkling fireworks have their own fragile beauty (see Figure 1). When we enjoy the fireworks on a summer night, we hold the top end of the paper string and ignite the lower end. Then, a small fireball is produced at the lower end of the paper string and beautiful streaks of light are scattered with soothing sounds. Some streaks of light burst secondarily downstream to produce streaks similar to pine needles. The lifetime of the firework is approximately 1 min. While the fireworks have been very popular in Japan, the physics behind the beauty was hidden mystery.

In the past, Terada1) was intensively interested in these physical and chemical phenomena. Nakaya and Sekiguchi2) investigated the relationship between sparks emitted during the grinding of iron and the amount of carbon inside. They also visualized sparkling fireworks and identified the importance of ambient oxygen and carbon in the black powder. Shimizu3) investigated the relationship between the compositions of black powder and resulting sparks, and reported that potassium sulfide was an important reaction product. Maeda and his high school students4) were the first to use X-rays to identify the internal structure of fireballs, and they conducted principal component analyses. Ito5) estimated a crystal

Figure 1 Self-luminous photo of sparkling fireworks.

Figure 2 Sparkling fireworks before ignition. Black powder is wrapped in paper at the left end. In use, the right end is held up with the left end at bottom to ignite.

structure of fireballs. Despite these previous studies, a comprehensible scenario has not been provided for the characteristic phenomena in sparkling fireworks because few clear visualization images were available. Recently, Inoue et al.[6)] emphasized the role of liquid atomization in sparkling fireworks, especially the origin of droplets from the fireball that will become streaks of light. However, the phenomena involved in secondary explosions of ejected droplets remain unclear. For better understanding, more detailed visualizations should be accumulated. In this study, a high-speed video camera was used to record the sequential atomization phenomena in sparkling fireworks more precisely than the previous report[6)], including not only ejection of droplets from the fireball but also explosion of the flying droplets. In Section 2, the experimental apparatus is introduced. In Section 3, the four-stage in a life of sparkling firework is explained. In Section 4, results of high-speed visualization measurements are discussed focusing on the process of droplet ejection from the mother fireball and that of droplet explosion downstream. In Section 5, conclusions are summarized.

2. Experimental apparatus

The sparkling fireworks used in this study were produced by Tsutsui-Tokimasa toy fireworks factory. A sample is shown in Figure 2. Self-luminous and shadow images were captured by a monochrome high-speed video camera, Photron SA-X. The typical frame rate and shutter speed were set 10,000 fps and 1/100,000 s, respectively. The image resolution was 1024×1024 pixels. A Nikon D 7000 camera was used to capture time-integrated images.

3. Sparkling fireworks

3.1 The life

A sparkling firework progresses through four seasons. They are traditionally referred to flowers as blossom buds, tree peony, pine needle, and falling chrysanthemum. Shimizu[7)] used an analogy to human life as infancy, young age, middle age, and old age. In this study, we simply call them as stages I-IV. Figure 3 shows time-integrated views of the four stages as we see in the eyes. In stage I, a spherical fireball is produced after ignition, but no sparks appear. After a few seconds, the firework enters stage II in which several sparks intermittently pop out from the fireball and explode at a distance. In stage III, the fireball is surrounded by many bright sparks. Finally, in stage IV, some short weak streaks are emitted. These four stages involve two types of atomization: primary atomization is ejection of sparks from the fireball and secondary atomization is explosion of sparks away from the fireball.

3.2 Chemical reactions and components

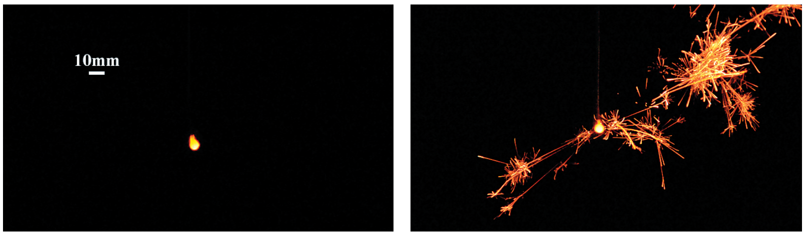
A chemical reaction of the black powder produces the fireball.

$$4KNO_3(s) + 7C(s) + S(s) \rightarrow 3CO_2(g) + 3CO(g) + 2N_2(g) + K_2CO_3(s) + K_2S(s) \qquad (1)^{8)}$$

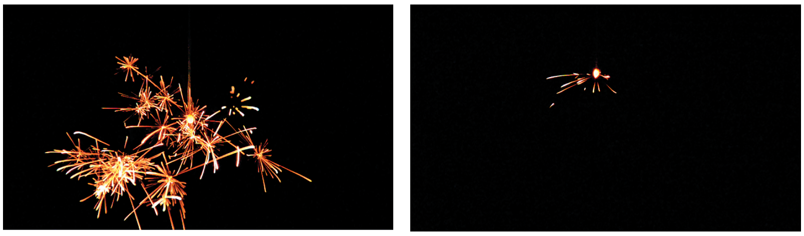
Inside the fireball, following chemical reactions produce gas and other compounds.

$$2K_2CO_3 + (2x+1)S \rightarrow 2K_2S_x + SO_2 + 2CO_2 \qquad (2)^{7)}$$

or



(a) stage Ⅰ (b) stage Ⅱ



(c) stage Ⅲ (d) stage Ⅳ

Figure 3 Self-luminous photos of four stages during the life of a sparkling firework[6)].

Table 1 Components of fireball.

Material	Formula	T_m [K]	T_b [K]	ρ [kg·m^{-3}]
Potassium sulfide	K_2S	1113	1185*	1800
Potassium carbonate	K_2CO_3	1164	*	2430
Potassium sulfate	K_2SO_4	1342	1962	2660
Potassium thiosulfate	$K_2S_2O_3$	–	–	–
Carbon***	C	3915**	–	–

*decomposition, **sublimation, ***graphite as reference
T_m : melting temperature, T_b : boiling temperature, ρ : density

$$8K_2CO_3 + (3x+1)S_2 \rightarrow 6K_2S_x + 2K_2SO_4 + 8CO_2 \qquad (3)^{5)}$$

$$4K2SO_4 + 7C \rightarrow 2K_2CO_3 + 2K_2S_2 + 5CO_2 \qquad (4)^{5)}$$

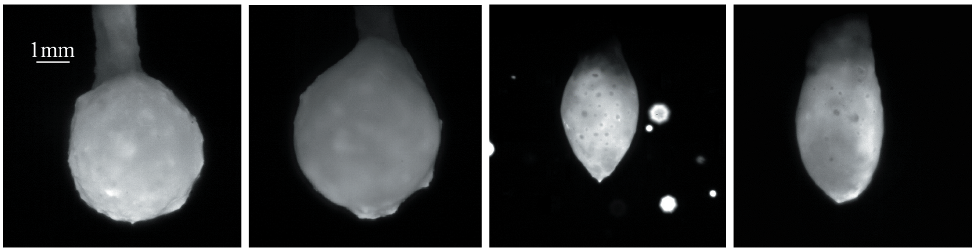
As shown in Table 1, the fireball consists of K_2CO_3, C, K_2S_x, K_2SO_4, and $K_2S_2O_3$[4]. In addition to the black body radiation from the fireball, luminescence spectrum due to potassium was measured[9]. It is assumed that the fireball is in molten salts containing solid particles with high melting temperature.

4. High-speed visualization

4.1 Fireball

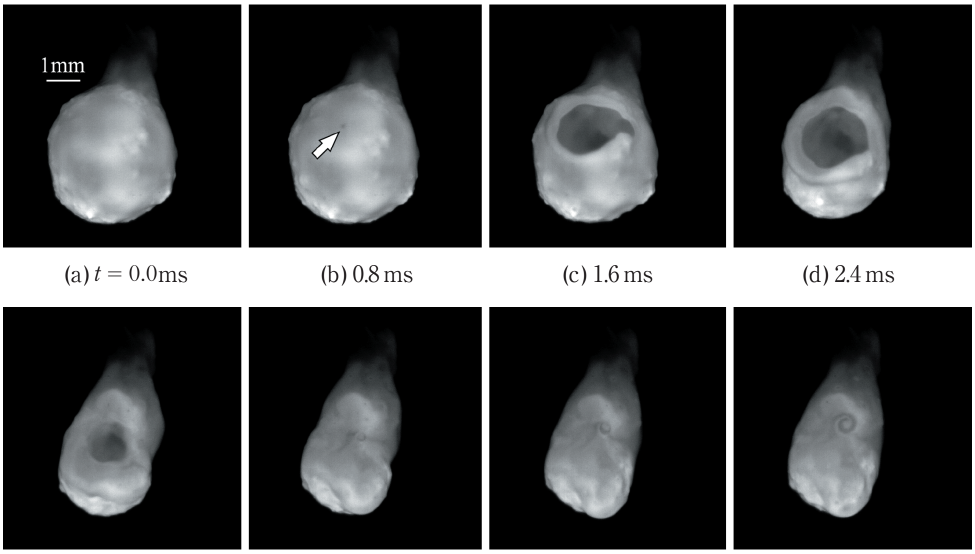
Figure 4 shows a fireball in each of the four stages at the bottom end of the paper string. In stages I and II, the fireball is nearly spherical with an outer diameter of 4 mm. The surface is lumpy and contains some bubbles, but it gradually becomes smoother as the solid part melts. In stages III and IV, the fireball becomes a spindle body with many bubbles on the smooth surface.

We now consider the unsteady phenomena that occur in each stage. Figure 5 shows self-luminous images of a fireball in stage I. The fireball, which is spherical at $t = 0$ ms, ruptures at $t = 0.8$ ms at the location indicated by the arrow. The rupture is quickly enlarged by the surface tension on the rim. From $t = 1.6$ to 3.2 ms, the cavity inside the fireball is clearly visible as also confirmed by X-ray diagnostics[4]. Figure 6 shows the temporal behavior of the fireball taken by a backlighting technique. At $t = 0$ ms, the pressure inside the fireball has become sufficiently high. At $t = 1$ ms, the fireball bursts and the contained gas rapidly erupts, as indicated by the arrow. The gas jet is a mixture of gases outside and inside the fireball. The ejection velocity is up to 10 m·s^{-1}. The fireball contracts until $t = 5$ ms, and then, from $t = 6$ to 7 ms, it gradually begins to expand. The fireball repeatedly expands and bursts as gas accumulates inside and collapses by losing the gas. Figure 7 illustrates a cross section of the fireball during the bursting process. In phase 1, the gas begins to be produced inside the fireball. In phase 2, the amount of gas and pressure inside the fireball increase. Suddenly, in phase 3, the surface of the fireball bursts at a position. The pressure is released, and the gas jet is ejected from the hole into ambient air. In phase 4, due to the surface tension, the rim of the hole is pulled into the fireball. The flows induced inside the fireball simultaneously concentrate to produce a small convex shape, but it is pulled back into the fireball. Finally, no droplets are



(a) stage Ⅰ (b) stage Ⅱ (c) stage Ⅲ (d) stage Ⅳ

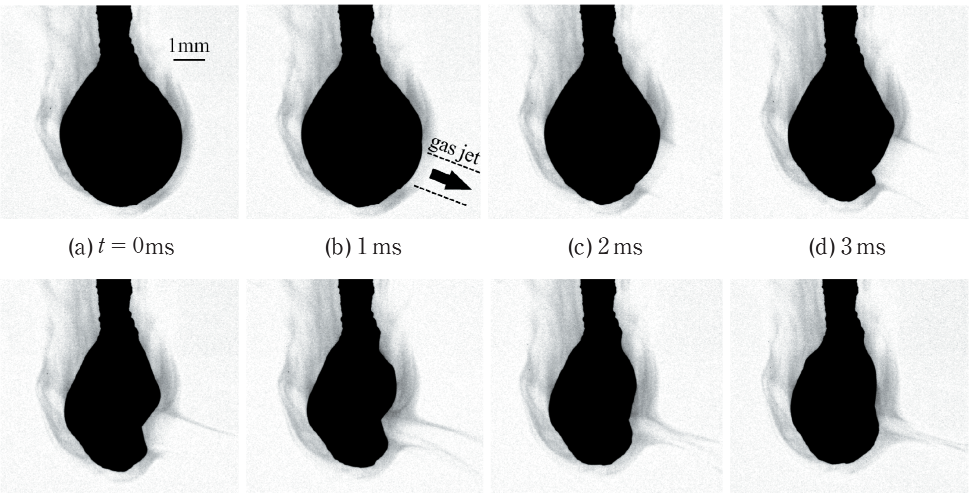
Figure 4 Shape of a fireball in each stage of its life. Each self-luminous photo represents a different firework.



(a) $t = 0.0$ms (b) 0.8 ms (c) 1.6 ms (d) 2.4 ms

(e) 3.2 ms (f) 4.0 ms (g) 4.8 ms (h) 5.6 ms

Figure 5 Self-luminous photos of a fireball bursting in stage I.



(a) $t = 0$ms (b) 1 ms (c) 2 ms (d) 3 ms

(e) 4 ms (f) 5 ms (g) 6 ms (h) 7 ms

Figure 6 Backlit photos of a bursting fireball with internal gas ejection in stage I.

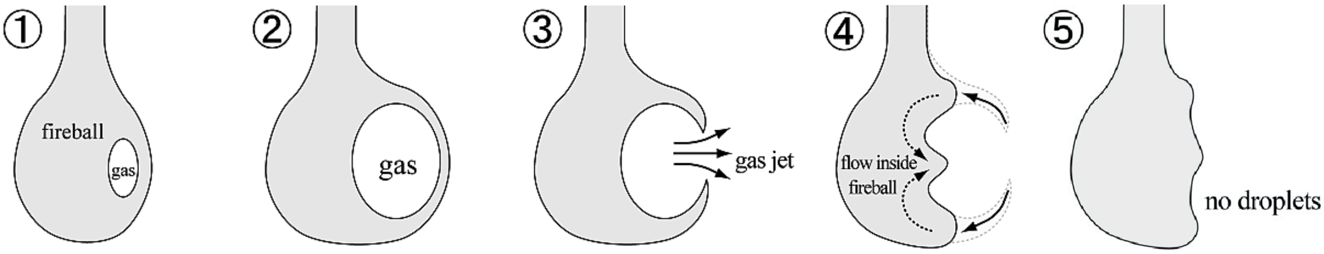
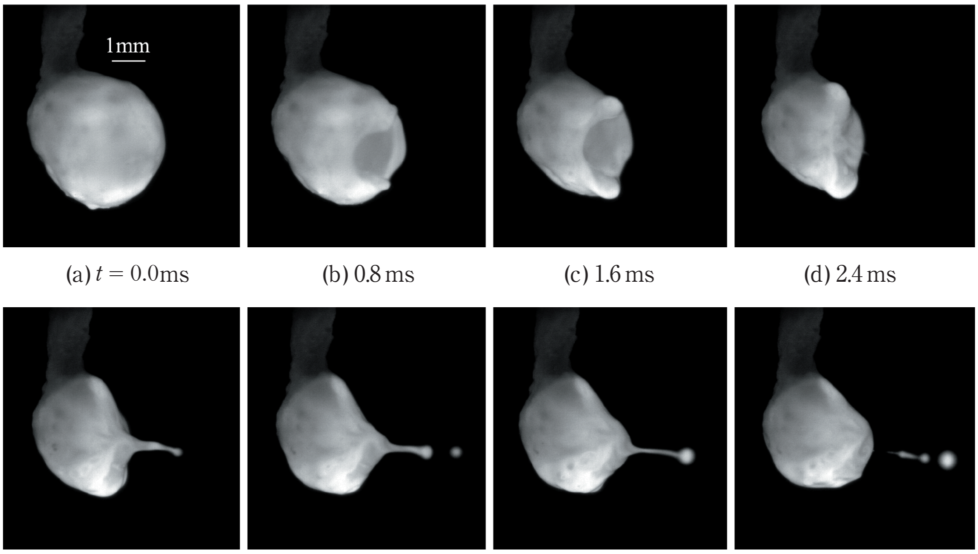


Figure 7 Cross sectional schematics of bursting fireball in stage I.



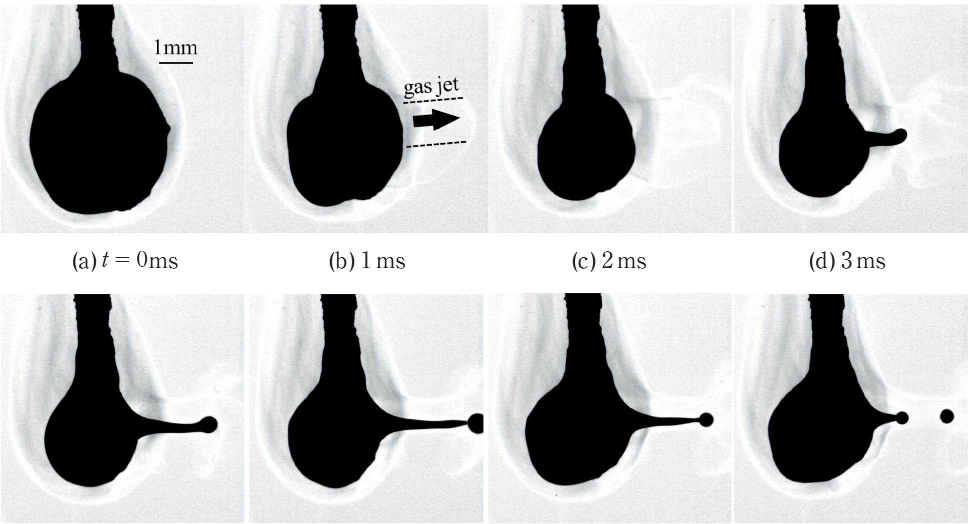
(a) $t = 0.0$ms (b) 0.8 ms (c) 1.6 ms (d) 2.4 ms

(e) 3.2 ms (f) 4.0 ms (g) 4.8 ms (h) 5.6 ms

Figure 8 Self-luminous photos of droplet generation in stage II.

ejected in phase 5.

Figure 8 shows self-luminous images of the fireball in stage II. The spherical fireball at $t = 0.0$ ms bursts on the right at $t = 0.8$ ms. The hole is enlarged due to the surface tension on the rim as in stage I. At $t = 2.4 - 3.2$ ms, a ligament of liquid begins to extend from the interior of the fireball. After $t = 4.0$ ms, the ligament breaks into several droplets to become streaks of light by surface reaction with ambient oxygen downstream. A bubble bursting on a liquid surface is subjected to a similar atomization process[10]. Figure 9 shows shadow images of the fireball. The expansion of the fireball reaches a limit at $t = 0$ ms. At $t = 1$ ms, it suddenly bursts and gas ejects indicated by the arrow. Then, at $t = 3$ ms, the ligament elongates toward the right. The ligament appears after the ejection of gas, and often comes out from a different position of gas ejection. Therefore, the ligament is not created by the gas jet[6]. During $t = 5 - 7$ ms, the ligament breaks into several droplets, and the root of the ligament is absorbed into the fireball. This atomization process repeatedly produces larger droplets than those produced in stages III and IV. These large droplets tend to suffer relatively smaller drag from ambient air than the tiny droplets. Hence, they can travel farther downstream and undergo secondary



(a) $t = 0$ms (b) 1 ms (c) 2 ms (d) 3 ms

(e) 4 ms (f) 5 ms (g) 6 ms (h) 7 ms

Figure 9 Backlit photos of bursting fireball and ejection of gas and droplets in stage II.

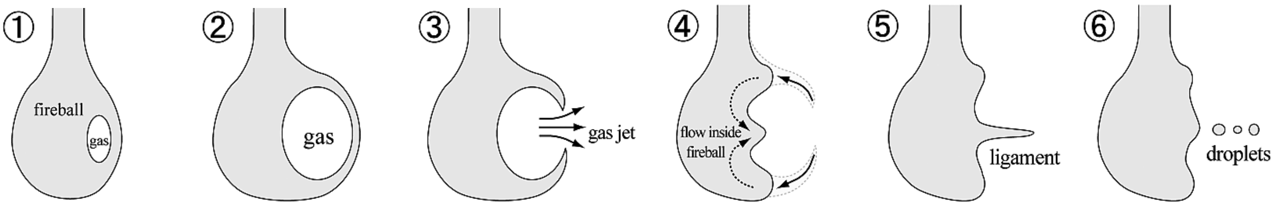
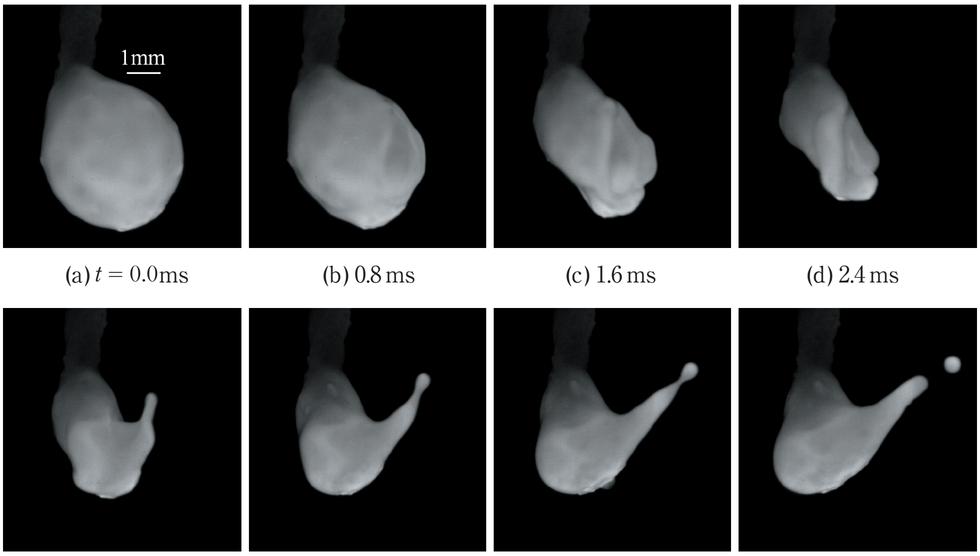


Figure 10 Schematics of droplet generation in stage II [6].



(a) $t = 0.0$ms (b) 0.8 ms (c) 1.6 ms (d) 2.4 ms

(e) 3.2 ms (f) 4.0 ms (g) 4.8 ms (h) 5.6 ms

Figure 11 Self-luminous photos of droplet generation enhanced by contracting the fireball in stage II.

explosions far from the fireball, as shown in Figure 3. The primary atomization process is illustrated in Figure 10. Phases 1-4 are similar to those in stage I. In phase 4, due to the surface tension, the rim of the hole is pulled into the fireball, and the flow concentrates to produce a convex shape at the bottom. The convex portion grows rapidly to become the ligament in phase 5. Finally, in phase 6, the ligament splits into droplets. The droplets originate from the interior of the fireball and not from its surface[6].

Figure 11 shows visualizations of a fireball with a thin surface during stage II. The same process is illustrated schematically in Figure 12. As the fireball itself contracts during $t = 0.8 - 2.4$ ms in Figure 11 (and equivalently during phases 3 and 4 in Figure 12), in addition to the flow into the fireball driven by surface tension, a thick ligament is created at $t = 3.2 - 5.6$ ms that produces larger droplets. Hence, two types of atomization processes occur in stage II as Figure 8 and 11.

In stages III and IV, the droplet ejection process is similar, as shown in Figure 13 and 14. Large deformations of the fireball as in stages I and II are gradually suppressed. Instead, small bubbles cover the fireball and burst. In Figure 13 (stage III), a bubble on the surface of the fireball bursts at $t = 0.1$ ms indicated by the arrow.

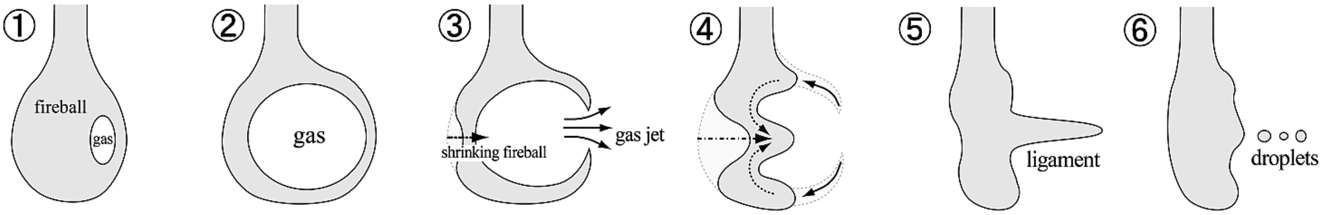
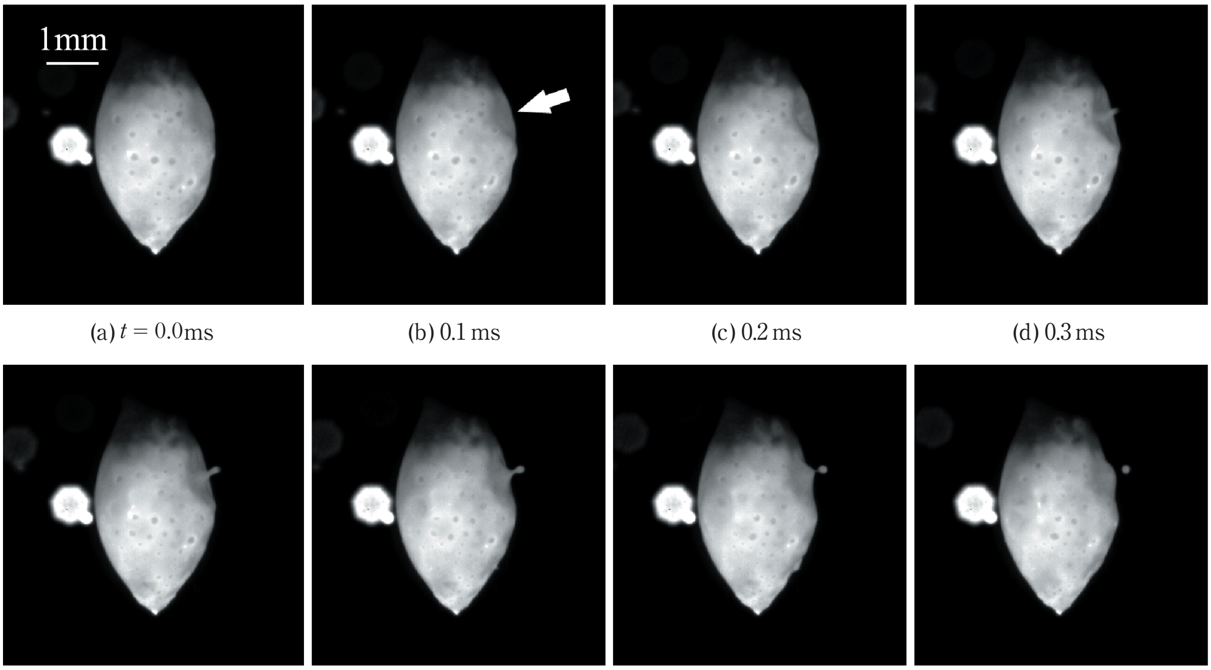


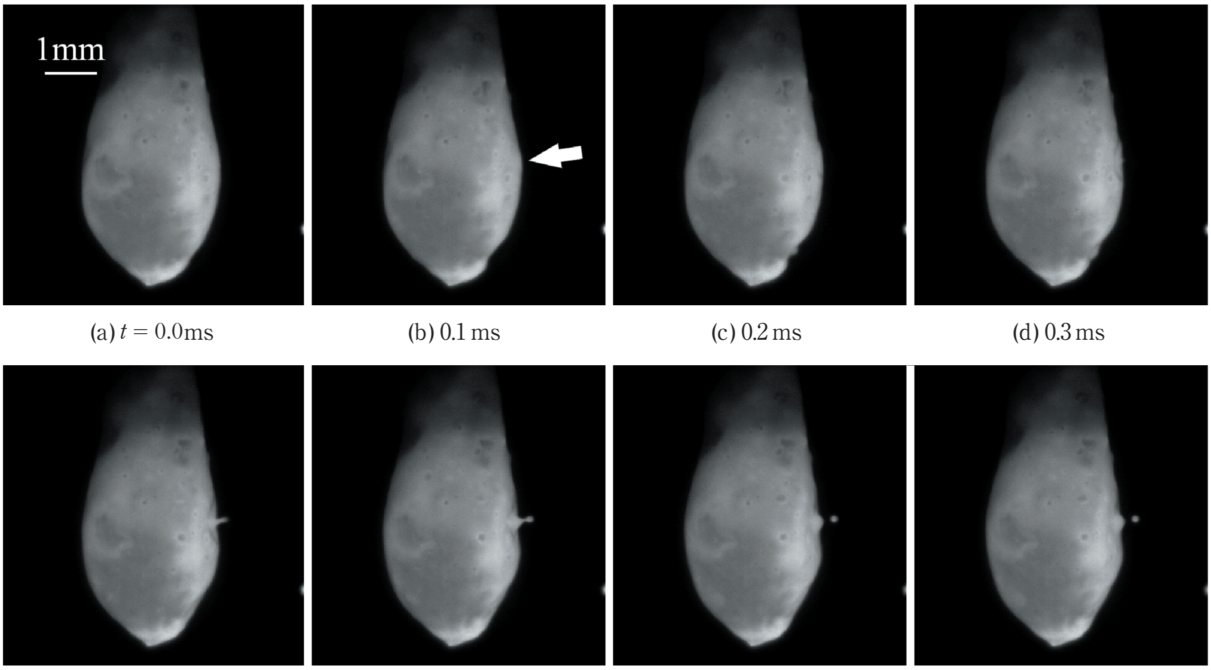
Figure12 Schematics of droplet generation enhanced by contracting the fireball in stage II.



(a) $t = 0.0$ms (b) 0.1 ms (c) 0.2 ms (d) 0.3 ms

(e) 0.4 ms (f) 0.5 ms (g) 0.6 ms (h) 0.7 ms

Figure13 Self-luminous photos of droplet generation in stage III.



(a) $t = 0.0$ms (b) 0.1 ms (c) 0.2 ms (d) 0.3 ms

(e) 0.4 ms (f) 0.5 ms (g) 0.6 ms (h) 0.7 ms

Figure14 Self-luminous photos of droplet generation in stage IV.

From $t = 0.3$ to 0.4 ms, a small ligament extends from the bottom of the bursting bubble. At $t = 0.6$ ms, the ligament breaks into a tiny droplet. In stage IV, some droplets are emitted from the bubbly fireball, as shown in Figure 14. This droplet generation process is illustrated in Figure 15. Although the bubble size is much smaller than the previous stage II, the mechanism of droplet ejection is consistently bubble bursting.

In the life of a sparkling firework, bubble bursting and the flow induced by surface tension are confirmed to be

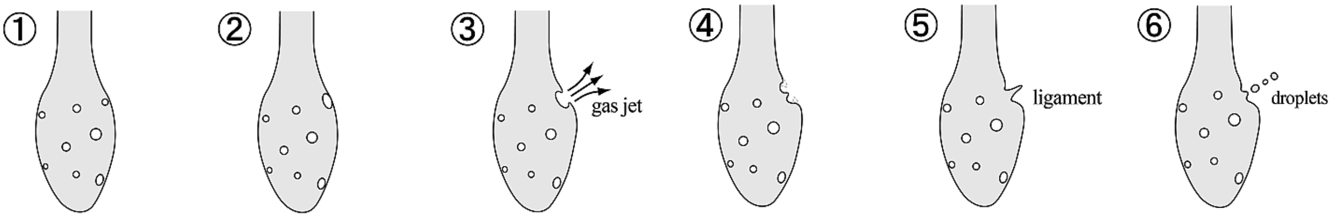


Figure15 Schematics of droplet generation in stages III and IV.

Table 2 Size and frequency of bubble bursting and droplet ejection.

Object			Stage I	Stage II	Stage III	Stage IV
Fireball	Diameter	[mm]	3~4	3~4	2*	2*
	Bursting freq.	[Hz]	10^1	10^1	–	–
Bubble on fireball	Diameter	[mm]	0.5	0.5	0.2	0.2
	Bursting freq.	[Hz]	$10^2 \sim 10^3$	10^2	10^3	10^3
Droplet ejection	Diameter	[mm]	–	0.5	0.1	0.1
	Ejection freq.	[Hz]	–	10^0	10^2	$10^1 \sim 10^2$
	Ejection velocity	[m·s^{-1}]	–	10^0	10^0	10^0

*In stages III and IV, the body is spindle–shaped with a horizontal diameter of 2 mm and vertical length of 4 mm.

essential for the droplet ejection. Droplets are always produced from the interior of the fireball and not from the surface. As shown in Figure 3(d), the streaks of light are not connected to the surface of the fireball because there is a time delay before the beginning of the chemical reaction between droplets and ambient oxygen.

Quantitative data measured from the visualization results are summarized in Table 2. In stages I and II, a relatively large fireball expands and contracts at a frequency of approximately 10 Hz, while in stages III and IV, the fireball itself does not move. Bubbles are always on the surface of the fireball. In stages III and IV, smaller bubbles frequently burst at 10^3Hz. After a bubble bursts, the surface of the fireball is renewed and has contact with fresh air, which produces several new bubbles. Droplets are ejected in stages II-IV. The largest droplets are emitted in stage II at 10^0Hz, while in stages III and IV, many small droplets are ejected at 10^2Hz. The velocities of ejected droplets are approximately 1 m·s^{-1}.

4.2 Spreading droplets

Figure 16 shows time series of the explosion process for a droplet emitted in stage III. The droplet behavior is the same as that in stage II. In each image, the fireball locates at the left end. The droplet, indicated by the arrow in Figure 16(a), is produced from the ligament after $t = 0.0$ ms. Until $t = 29.8$ ms, the droplet spreads while keeping its original shape, but the surface temperature seems to increase because its color gets brighter. The droplet suddenly expands at $t = 29.9$ ms, and bursts at $t = 30.0$ ms ejecting gas toward the right. The gas ejection balances the inertial force of the droplet, and its horizontal motion stops. The droplet deforms at $t = 30.1$ ms and contracts releasing several tiny droplets at $t = 30.2$ ms. Each tiny droplet becomes a pine needle-like spark. During $t = 30.3 - 30.9$ ms, the droplet expands and contracts several times. Then, at $t = 31.0$ ms, three smaller droplets are created. They also expand and contract to emit several droplets. Gas production inside the spreading droplet is considered to be the essential factor for the secondary explosions.

Figure 17 shows the time variant diameter d [m] of the droplet indicated by the arrow in Figure 16 against the initial diameter d_0 [m], which is defined as the one just after ejection. Since the value keeps $d/d_0 \simeq 1$, the droplet is non-evaporative. It flies for a while and the surface suddenly puffs at $t = 28.2$ ms. After that, the droplet suddenly expands more than twice the diameter at $t = 29.9$ ms (see Figure 16(f)) and bursts at $t = 30.0$ ms (Figure 16(g)) by the inner gas production. From the detailed visualization results, the secondary atomization is caused by microexplosions[11]. However, well-known microexplosion occurs on an evaporative droplet, and therefore the gas production mechanism in the fireworks should be different and is an open question.

5. Conclusions

Detailed high-speed visualization measurements of a life of sparkling fireworks were carried out by using a high-speed video camera. Both the mother fireball and subsequent spreading droplets were investigated. Conclusions are summarized as follows.

(1) Liquid atomization due to bursting bubbles was confirmed to be essential for the droplet ejection. The gas ejection from the bubble didn't blow off the droplets.
(2) The non-evaporative droplets suddenly expanded and contracted to produce some secondary droplets.

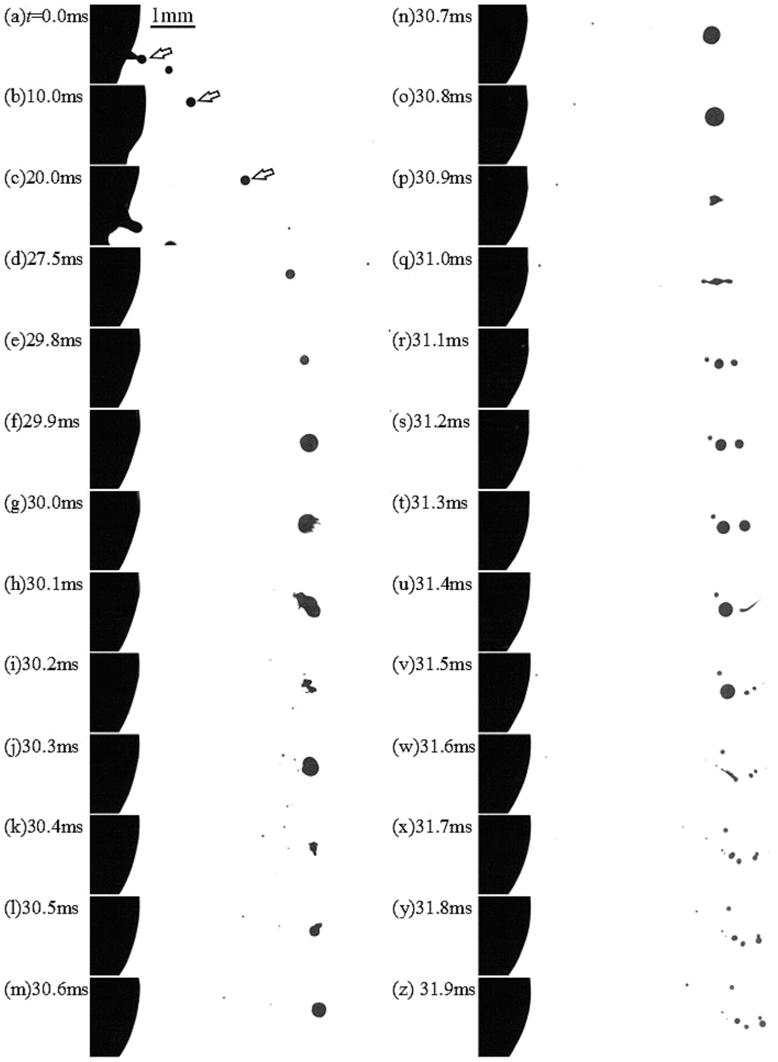


Figure16 Backlit photos of secondary explosions of ejected droplets in stage III.

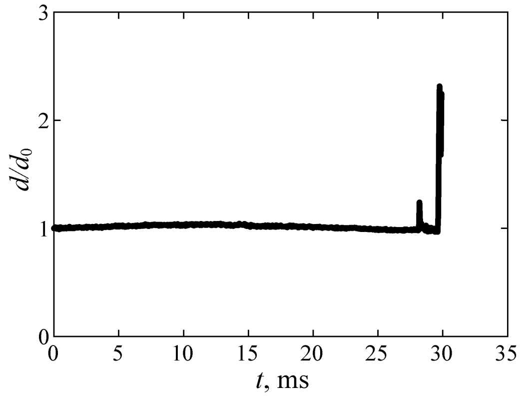


Figure17 Time-variant ratio of droplet diameter to the initial one. ($d_0 = 0.17$mm)

(3) In the first-half of a sparkling firework's lifetime, droplets were produced at 10^0Hz by the flow driven by the surface tension resulting from the bursting fireball.

(4) In the last-half of the lifetime, the fireball deformed slightly and small bubbles frequently burst on its surface. Bubble bursting on the surface of the fireball produced many droplets at 10^2Hz.

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