Letter

Origin of droplets in sparkling fireworks

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Received : November 18, 2012 Accepted : January 21, 2013

Abstract

The physics behind the beauty of sparkling fireworks has not been clarified yet due to a lack of detailed visualization results. In the present study, atomization process in sparkling fireworks is elucidated by using a high-speed video camera. In the first-half sequence of the fireworks, the fireball repeatedly expands, bursts, and shrinks due to the high pressure gas inside the fireball. In contrast, in the last-half sequence, the bubbly fireball slightly deforms, and small bubbles burst on the fireball. A scenario of droplets generation is as follows : a liquid thread extends from the bottom of the bursting fireball, and fragments into droplets. Thus the droplets originate from inside the fireball rather than from its surface.

Keywords : sparkling firework, high-speed video camera, visualization, atomization, bursting bubble

1. Introduction

Sparkling fireworks are composed of a black powder, which is a mixture of potassium nitrate, carbon and sulfur, simply wrapped in a twisted paper. The fireworks scatter beautiful streaks of light with soothing sounds. The formation of these streaks is attributed to sequential atomization and luminescence of droplets ejected from the fireball driven by a series of chemical reactions. In the past, T. Terada[1] was intensively interested in these physical and chemical phenomena. In 1927, U. Nakaya and Y. Sekiguchi[2] investigated the relationship between the sparks emitted during the grinding of iron and content rate of carbon in the iron. They also visualized the sparkling fireworks, and pointed out the importance of carbon in the black powder and ambient oxygen. T. Shimizu[3] investigated the relationship between the composition of black powder and sparks. A. Maeda et al.[4] identified the internal structure of the fireballs using X-rays, and conducted principal component analysis. H. Ito[5] estimated the crystal structure of the fireball. Despite these previous studies, a lucid scenario has not been provided for the characteristic phenomena in sparkling fireworks, which are the sequential atomization and luminescence process. In this study, by using a high-speed video camera, an atomization process in sparkling firework is visualized, and the origination of droplets from the fireball is clarified.

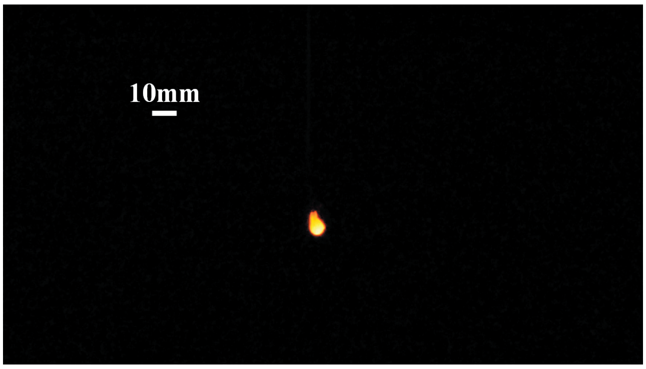
2. Experimental apparatus

Sparkling fireworks produced by Tsutsui-Tokimasa gangu-hanabi seisakusyo was utilized. During combustion, both self-luminous images and shadow images were taken by a high-speed video camera, Photron SA-X. Typical frame rate and shutter speed were set to 10,000fps and 1/100,000s, respectively. The image resolution was 1024×1024pixels. A NIKON D7000 camera was also used to capture the time integrated images.

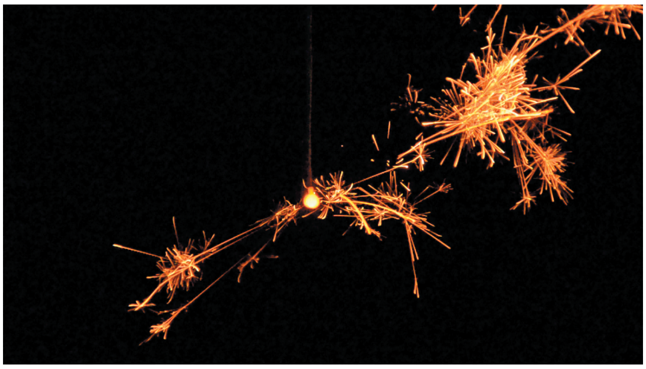
3. Results and discussions

Sparkling fireworks involve four stages. They are called by an analogy to flowers[1] or human beings[6] : blossom buds / tree peony / pine needle / falling chrysanthemum or infancy / young age / middle age / old age. In this study, these four stages are simply called from stage 1 to stage 4. Figure 1 shows the time integrated views of the four stages. First, in stage 1, a spherical fireball is produced. No sparks appear in this stage. After a few seconds, in stage 2, several sparks pop out intermittently from the fireball, and explode at a distance. Then, in stage 3, the fireball is surrounded by a number of bright sparks. Finally, in stage 4, short streaks are weakly emitted. Thus, two types of atomization are confirmed ; the primary one is ejection of sparks from the fireball, and the secondary one is explosion of sparks away from the fireball.

The unsteady phenomena are explained for each stage.

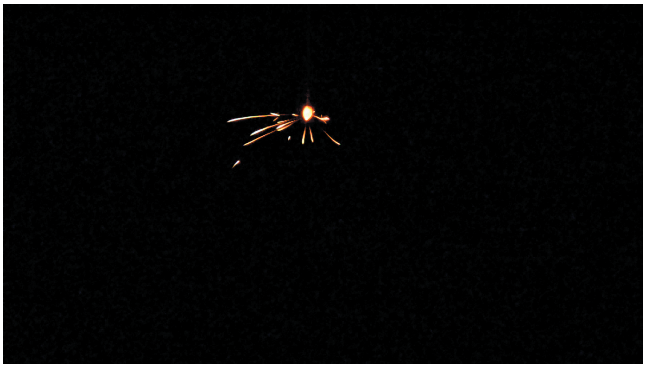


(a) stage 1



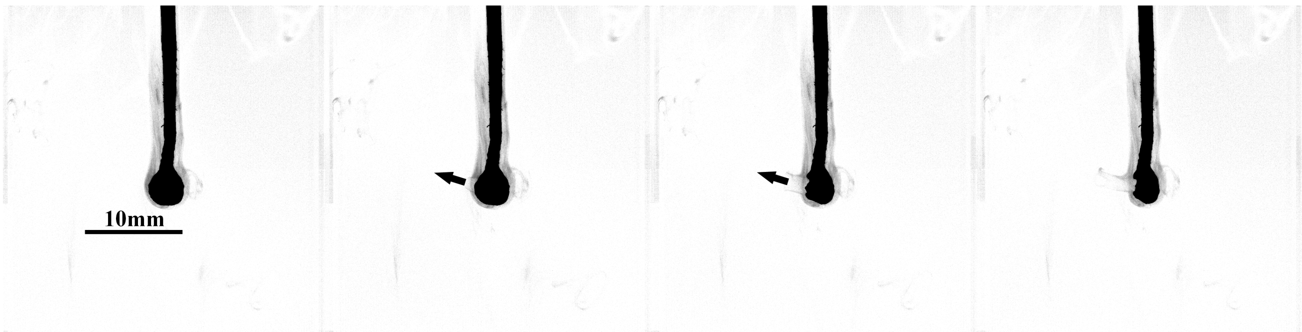
(b) stage 2

(c) stage 3

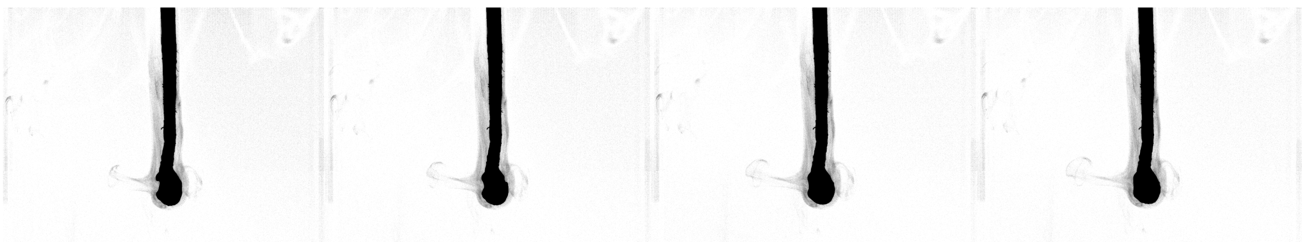


(d) stage 4

Figure 1 Four stages of sparkling fireworks



t = +0 ms +1 ms +2 ms +3 ms



+4 ms +5 ms +6 ms +7 ms

Figure 2 Stage 1 : Cycle of expansion, burst and shrink of a fireball.

Figure 2 shows the time-series behavior of the fireball in stage 1 taken by the high-speed video camera by backlighting technique. In this stage, no atomization occurs. At t=+0 ms, the diameter of the fireball is approximately 4 mm. The fireball consists of K_2CO_3, C, S, K_2SO_4, and K_2SO_3[4]. Inside the fireball, high pressure gas is trapped, which is considered as CO_2 in main produced by the following chemical reactions :

$$2K_2CO_3+(2n+1)S \rightarrow 2K_2S_n+SO_2+2CO_2, \quad (1)^{6)}$$

or,

$$8K_2CO_3+(3n+1)S2 \rightarrow 6K_2S_n+2K_2SO_4+8CO_2, \quad (2)^{5)}$$

$$4K_2SO_4+7C \rightarrow 2K_2CO_3+2K_2S_2+5CO_2. \quad (3)^{5)}$$

When the pressure inside the fireball becomes

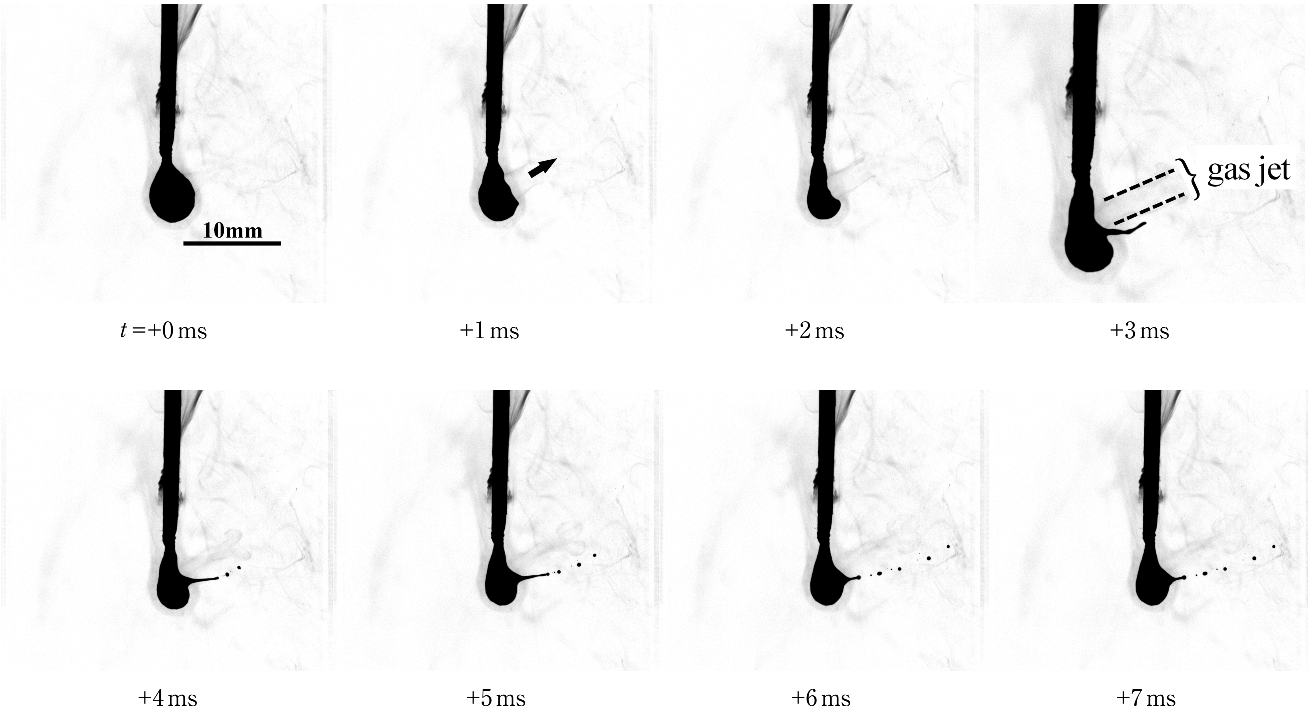


Figure 3 Stage 2 : Time series of the bursting fireball and ejection of droplets.

sufficiently high, the fireball bursts and the contained gas rapidly erupts as indicated by the arrow at t =+1 ms and +2 ms. The gas jet is mixture of the gas outside the fireball and the gas inside. The ejection velocity is approximately 1 m·s^{-1}. From t =+3 ms to +7 ms, the shrunk fireball gradually recovers to its spherical shape. Then, the fireball repeatedly expands and bursts due to the gas inside. These visualizations indicate that the fireball is in liquid state.

Figure 3 shows the primary atomization process in stage 2. The expansion of the fireball reaches a limit at t = +0 ms. The fireball suddenly bursts at t =+1 ms accompanied by the gas jet ejected with a speed of 1 m/s as illustrated by the arrow. Then, at t =+3 ms, the liquid thread elongates with a speed of 4 m/s toward the right hand side in the picture. Since the gas jet and the thread are oriented in different directions, the thread is not created by the gas jet. During t =+4 ms~+7 ms, the thread breaks into several droplets flying at a velocity of 3 m/s. The root of the thread is absorbed into the fireball. This atomization process repeatedly produces larger droplets than in following stages 3 and 4. The large droplets tend to suffer a relatively smaller drag by the ambient air than tiny drops, and reach further downstream. At far away from the fireball, droplets secondarily explode as shown in Figure 1.

Figure 4 shows self-luminous pictures of stage 2. The spherical fireball at t =+0 ms bursts at the right bottom at t =+0.4 ms. The hole is enlarged by the surface tension on the rim, which is similar to the case of a bursting soap bubble. The thread begins to extend from the interior of the fireball at t =+2.0~+2.4 ms. At t =+2.8 ms, the droplet breaks from the thread. A bubble bursting on a liquid surface is subjected to a similar atomization process[7].

The primary atomization process is illustrated in Figure 5, which shows the cross section of the fireball. First in phase①, CO_2 begins to be produced inside the fireball. In phase②, the amount of gas and the pressure inside the fireball increase. In this phase, however, the pressure is in equilibrium between gas bubble and surrounding liquid inside the fireball. Suddenly, in phase③, the surface of the fireball bursts. The pressure is released, and the gas jet is ejected from the hole into the ambient air. Then, 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 at the bottom. Because the pressure inside the fireball is higher than that of the ambient gas, the convex portion grows rapidly to become the thread as shown in phase⑤. Finally, in phase⑥, the thread splits into droplets. It was revealed that the droplets originate from the interior of the fireball, and not from its surface.

Figure 6 shows the primary and secondary atomization processes in stage 3. From stage 3 to stage 4, the large deformation of the fireball is gradually suppressed. Instead, small bubbles cover the fireball, and each one bursts. In stage 3, numerous small particles are emitted, and they secondarily explode at a distance, which can be confirmed in t =+0~+5 ms. From t =+5 ms to +7 ms, a small droplet is ejected from the small bubble bursting on the fireball, which is indicated by the white arrow. It can be confirmed that there is the depression of the fireball on its left-hand side (t =+5 ms) and the ligament (t =+6 ms). Thus, this mechanism of primary atomization is consistent with that in stage 2. In each case, the essential phenomenon is the bursting of the fireball or bubble. The secondary rupture process of the droplet appears to be different from the primary atomization process, but this has not been clarified yet.

Finally, Figure 7 shows the droplet ejection process in

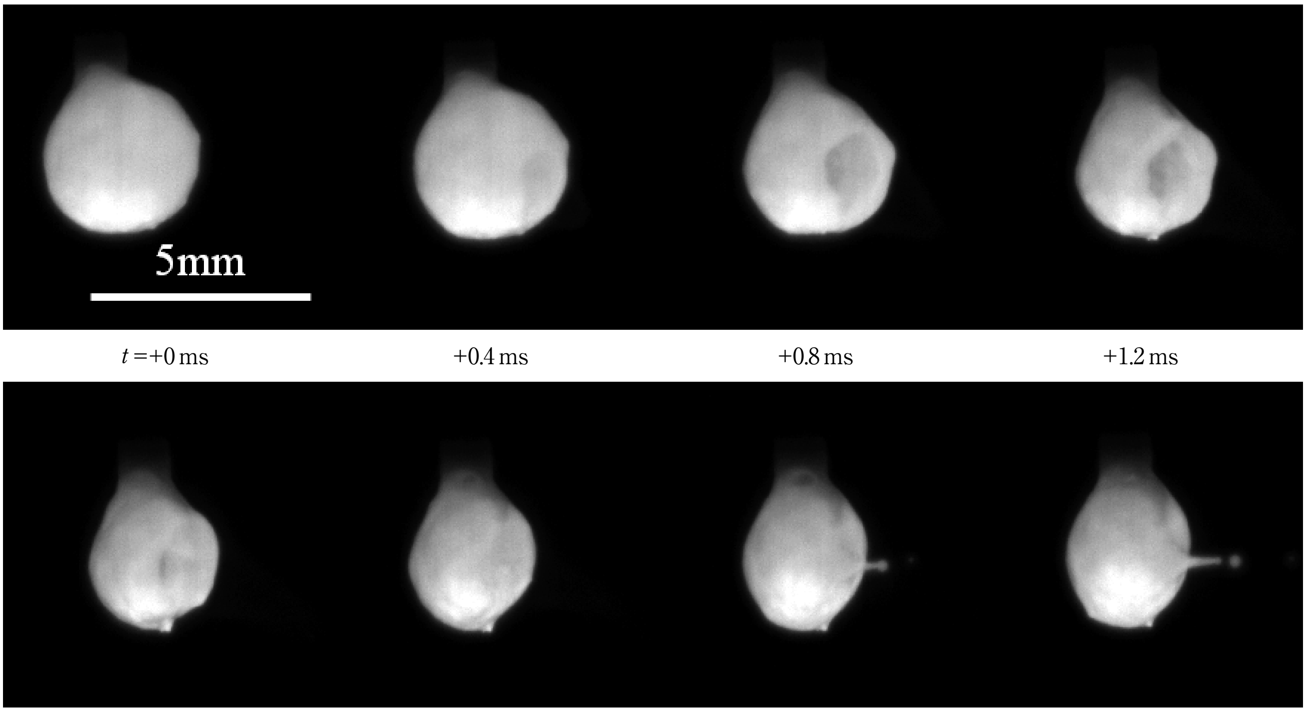


Figure 4 Stage 2 : Droplet generation process.

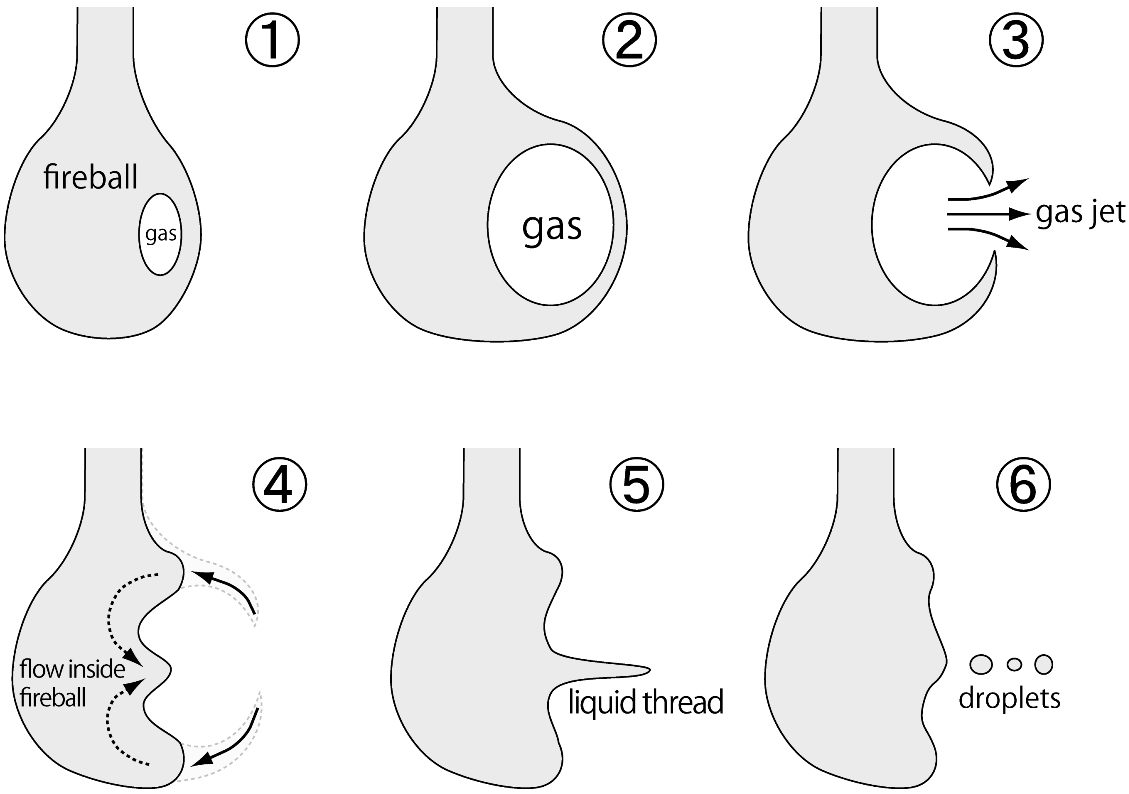


Figure 5 Stage 2 : Schematic of droplet generation process.

stage 4. Small number of droplets is emitted from the bubbly fireball as shown in Figure 8. The secondary explosion of droplets does not occur frequently. Even in this stage, the mechanism of primary atomization is the same as that in stage 2. Stage 4 of Figure 1 indicates that the streaks of light originate not from the fireball but at a distance, because the ejected droplet is produced from the interior of the fireball and there is a time delay until the beginning of chemical reaction of droplet with ambient oxygen. If each emitted droplet emerges from the surface of the fireball, the streak should have its root on the surface.

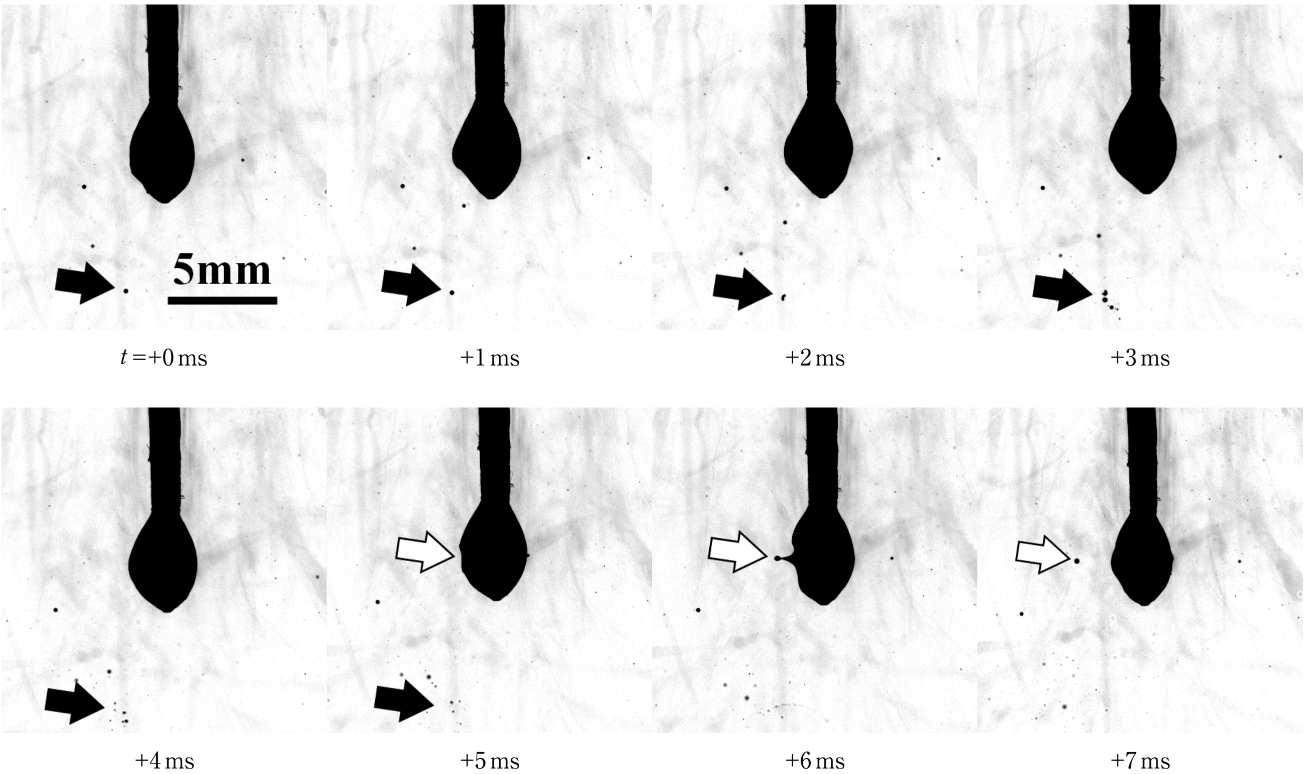


Figure 6 Stage 3 : Droplets ejection and their secondary explosion.

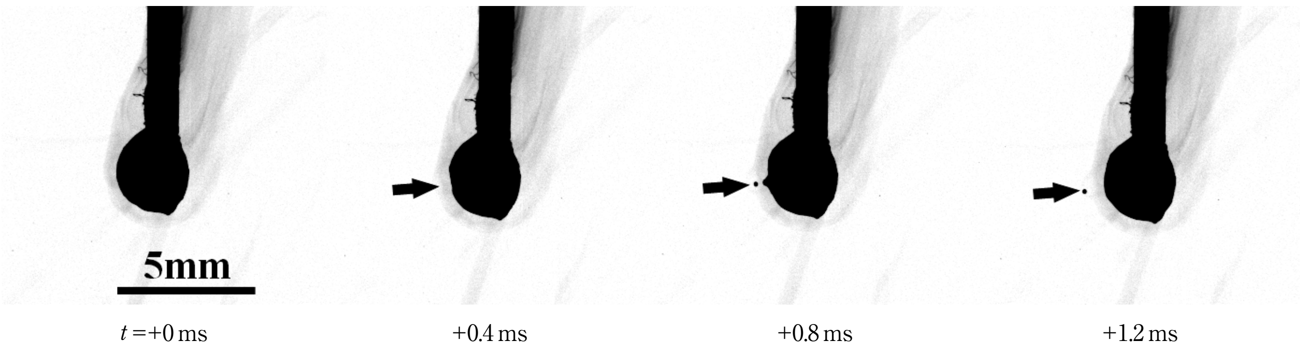


Figure 7 Stage 4 : Droplet ejection.

4. Conclusions

Sparkling fireworks were visualized by use of a high-speed video camera. Conclusions are summarized as follows.

(1) In the first-half sequence of the fireworks, the fireballs repeatedly expanded, burst and shrunk due to the high pressure gas produced inside the fireballs. In the last-half sequence, the fireballs slightly deform, and small bubbles burst on the fireball.

(2) A scenario of droplets generation from the fireball is as follows : the liquid thread elongates from the bottom portion inside the bursting fireball, and the thread fragments into droplets. Therefore, droplets originate inside the fireball rather than from its surface.

In the present study, the process of droplet ejection was elucidated, in which the essential phenomenon was the bursting of fireballs or surface bubbles. Instead, the mechanism of secondary explosion of sparks is still an open question.

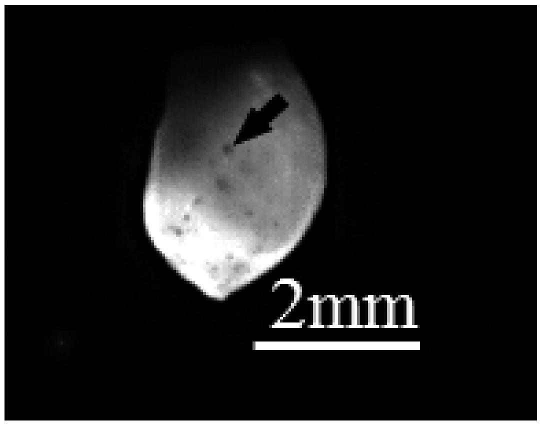


Figure 8 Stage 4 : Foamed fireball. The arrow indicates a bubble.

Acknowledgement

We would like to thank Dr. Shuji Hatanaka of Japan Pyrotechnics Association for his valuable comments and Dr. Joji Kuwabara of Photron Ltd. for his kind cooperation in the experiment.

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線香花火における液滴放出機構

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線香花火における物理的・化学的事象には未解明な点が多い。本研究では，ハイスピードカメラを用いて，線香花火の時系列の自発光写真と背景散乱光影写真を取得することで，一連の非定常現象を明らかにした。花火の前半では，大きな火球が形成され，内部に発生したガスによる膨張と破裂，そしてガス噴出に伴う収縮を繰り返す。一方，後半では，火球本体の大変形は抑制され，火球表面にある多数の泡が弾ける。こうした火球からの一次的な液滴生成は，火球本体あるいは火球表面の泡の破裂に伴って，火球内部から伸長した液糸が分裂して起きることが明らかになった。即ち，火弾は火球表面ではなく，火球内部から生じる。

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