How Does Senkou-hanabi Fire in 10T Magnetic Field?

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(Received March 9, 1998; CL-980167)

The magnetic field effect to a traditional Japanese firework; Senkou-hanabi, was investigated by using a superconducting magnet. The lifetime of burning Senkou-hanabi was changed by the magnetic volume force induced by the gradient magnetic field.

The recent development of a superconducting magnet enables us to observe interesting magnetic field effects even for materials of very small magnetic susceptibility.[1-4] We have investigated the magnetic effect for burning of Senkou-hanabi, which consists of powdered potassium nitrate, sulfur, and carbon. These are wrapped in a paper and a paper string hangs it at the bottom. Once the Senkou-hanabi is ignited, red flame appears downward at first, and after that, a red fireball is formed at the bottom of the paper string. For a short time, nothing seems to happen while the fireball matures. After the color of the fireball changes into a little yellow, suddenly a first fire-grain is launched like an arrow and a lot of the fire-grains are shot one after another. Almost all of them split into several smaller ones. After passing through this vigorous stage, the fireball shrinks into a small black ball.

The key reaction for the combustion of Senkou-hanabi is represented as follows;[5]

$$2KNO_3 + 2C + 1/2O_2 \text{ ----->} K_2CO_3 + CO_2 + 2NO \quad (1)$$

The fractal structure of the flying grain is qualitatively explained by a cascade explosion, which is controlled by a diffusion of oxygen through a skin of a molten potassium carbonate. Estimated by the color of the light emission, the surface temperature of the ball is above 900 °C, which is over the melting point of potassium carbonate of 898 °C. The melt covers the core, which consists of carbon and potassium nitrate and these have not reacted yet. The surface tension of the melt forms the spherical shape of the ball. As Oxygen diffuses into the core, potassium nitrate and carbon start to react and generate the gases of carbon dioxide and nitric oxide. When the inner pressure surpasses the atmospheric pressure, the ball splits like a moderate explosion.

Senkou-hanabi were set in the bore of a magnet, and the variations of the magnetic field strength in the horizontal x and y direction were less than 5 %. The strongest field in z direction was 10 T at the center and the field strength of z direction was changed as schematically shown in Figure.1. A product of the magnetic field and the field gradient, $B_z(dB_z/dz)$ had a maximum of 450 T^2/m at the place of ± 7 cm from the center. In order to initialize the combustion condition for every experiment, the air in the bore was blown out whenever the firework finished. The magnetic field was varied from 0 T to 10 T. The every event was recorded by a video camera as shown in Figure 1.

Unfortunately, any unambiguous difference in the shape

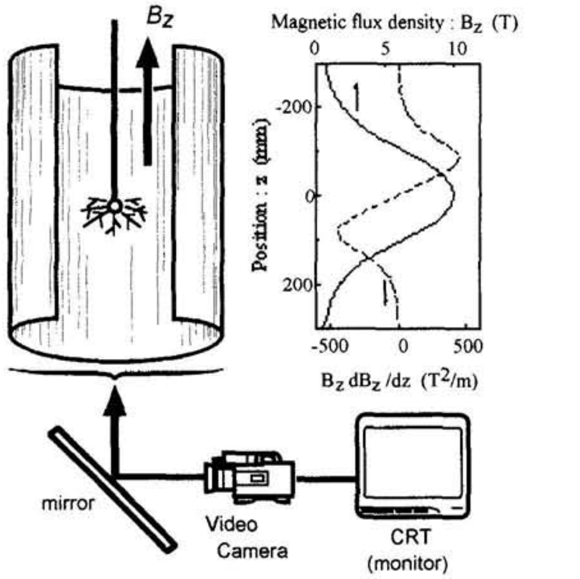

Figure 1. Schematic representation of an experimental setup and B_Z distribution in a superconducting magnet.

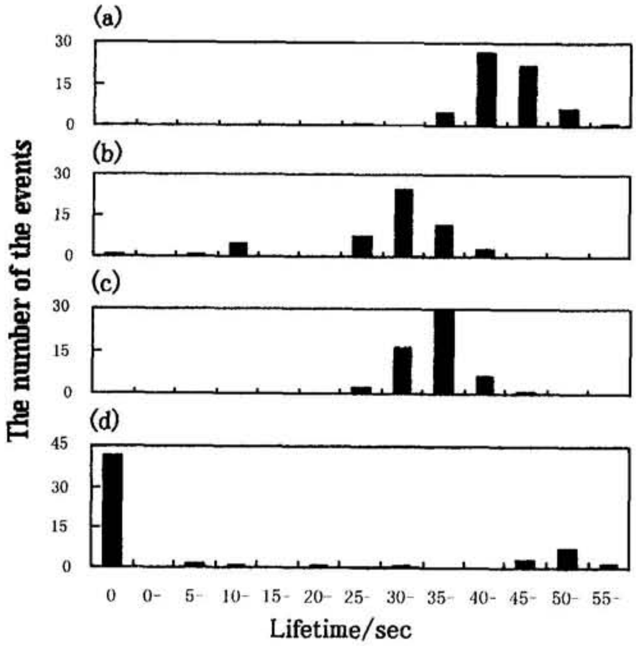

Figure 2. Lifetime distribution of Senkou-hanabi under (a)0 T at the center, under 10 T at the position of (b)-7 cm, (c)0 cm, and (d)+7 cm from the center.

of the burning was not observed under 0 T and up to 10 T. However, the lifetime of Senkou-hanabi was affected by the magnetic field. The histogram of the lifetime under 0 T and 10 T is shown in Figure 2 as a function of the position of Senkou-hanabi.[6] The initial time, zero was assigned to the time when the fireball formed completely. The end of the life was defined as the time when the fireball became black. Under 0 T, the peak of the lifetime was 43 s at the center in the bore. Under 10 T, the peak of the lifetime were changed as the burning position, which are shown in Table 1. The lifetime were investigated at three

Table 1. Lifetime distribution of Senkou-hanabi

Position[a] /cm	Magnetic field strength /T	Lifetime /s
0	0	43
-7	10	31
0	10	38
+7	10	54

a The distance from the center. The upper direction is assigned to minus, *vice versa*.

positions which located at the center and the positions of ±7 cm from the center. Under 10 T, although there was a large deviation from the normal distribution, the peak of the lifetime was 38 s, 31 s and 54 s at the burning positions of the center, 7 cm higher form the center and lower from the center, respectively. Moreover, at the position of 7 cm lower from the center, over the half of the events had the lifetime of zero. This finding indicates that the fireball drops immediately just after the formation of the ball at the position.

These results that are the variation of the lifetime and the sudden drop of the fireball are explained by the magnetic force induced by the gradient magnetic field. In the magnetic field, the material whose magnetic susceptibility per unit volume is χ is affected by the force from the field as[7,8]

$$F = \chi\ V(B_z/\mu_0)dB_z/dz \qquad (2)$$

where μ_0, V and B_z are the magnetic permeability of the vacuum, the volume of the material and the magnetic field strength, respectively. The fireball of Senkou-hanabi is sustained by the balance between the surface tension and the gravitational force. When the magnetic field is applied, the magnetic force is superposed. Thus, there must be a critical volume V_0, over which the fireball drops from the string.[9]

$$V_0 = 2\pi R\gamma/\{\rho g + (B/\mu_0)\chi\ dB_z/dz\} \qquad (3)$$

where R, γ and ρ are the radius of the cross section of a neck where the ball sticks to the string, the surface tension around the neck and the density of the ball, respectively. As the fireball is a diamagnetic material, the magnetic volume force affects to pull up and pull down the ball at the position of higher and lower from the center, respectively. The critical volume at the position lower from the center must be smaller than the one at the higher and the center position. Thus, the large amount of lifetime zero events were obtained in Figure 2 (d).

The survived ball gradually heats the air nearby and expands the volume. The local heating of the air in the bore is known to induce flow of the magnetic convection as well as of the thermal convection.[10] This forms the spatial gradient of the magnetic susceptibility, which is determined by the density of the oxygen. As shown in Eq.(2), the magnetic force to the air becomes asymmetric under this condition, and it induces the flow. The direction of the magnetic convection is parallel to the direction of the thermal convection when Senkou-hanabi is placed above the center. However, it is anti-parallel below the center. Then, above the center, the two concerting flow of the air increases the transportation of the oxygen to the reacting core in the ball. But, below the center, the competition of the flow decreases the oxygen transport. Thus, in the case of Figure 2 (b), the reaction (1) occurs vigorously and the lifetime of the ball must be shortened. But, below the center, the life time must be enlarged as shown in Figure 2(d).

Reference and Notes

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