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微小重力場における冷炎を考慮した液滴列の燃え広がり形態に関する研究

Study of mode of flame spread over droplet arrays considering cool flame in microgravity

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1. Introduction

Spray combustion is used for diesel engines and gas turbines. In this method, liquid fuel is atomized through a fuel injection nozzle and is ignited. Since multiple physical and chemical processes occur at the same time and in a short time, its mechanism is very complicated and there are many points that have not been clarified. Clarification of the mechanism will contribute to an improvement of combustion efficiency and simulation accuracy. In order to research spray combustion from a fundamental viewpoint, we use fuel droplet arrays with a diameter of several hundred μm so that we can obtain enough spatial and temporal resolutions. With such droplet diameters, however, it is difficult to get rid of the effect of natural convection, and therefore we have conducted experiments in microgravity.

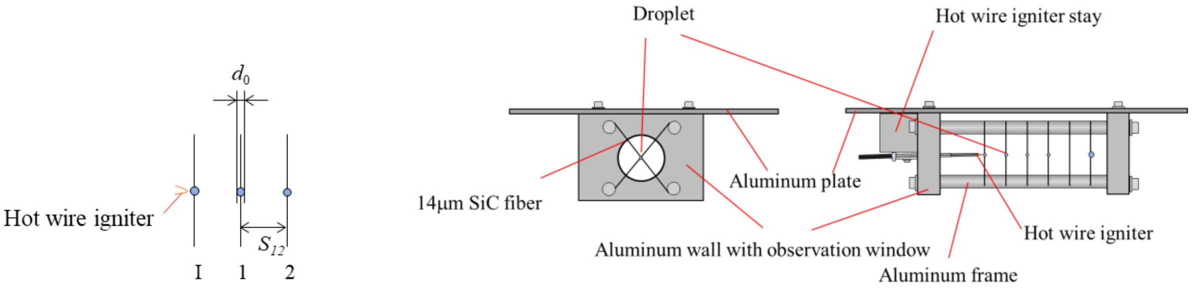
Mikami et al. 1) experimentally investigated the flame-spread mode using liner droplet arrays in microgravity. They focused the flame spread behavior between droplets and classified it as several flame-spread modes. However, they didn't consider the cool flame, which is a low-temperature oxidation reaction from 580K to 750K occurring for hydrocarbon fuels. Researchers have paid attention to this phenomenon because it may affect combustion dynamics and efficiency. Tanabe et al. 2) investigated the self-ignition behavior of *n*-heptane, *n*-dodecane, and *iso*-octane for different ambient gas temperatures and pressures in normal gravity. They found four types of self-ignition modes: single-stage ignition only with the cool flame; single-stage ignition only with the hot flame; two-stage ignition, the cool flame first appears and then transits to the hot flame; and no-ignition. These results showed that the cool flame can be observed not only in premixed combustion but also in droplet combustion. Mikami et al. 3) investigated the appearance of cool flame during flame spread between droplets using droplet-cloud elements. A mid-wave infrared camera captured the infrared luminescence around droplets without the hot-flame appearance, the luminance which is caused by combustion products of cool flame.

Based on these results, this study redefines the flame-spread mode considering cool flame and clarifies the condition of cool flame appearance.

2. Experimental Apparatus and Analysis Method

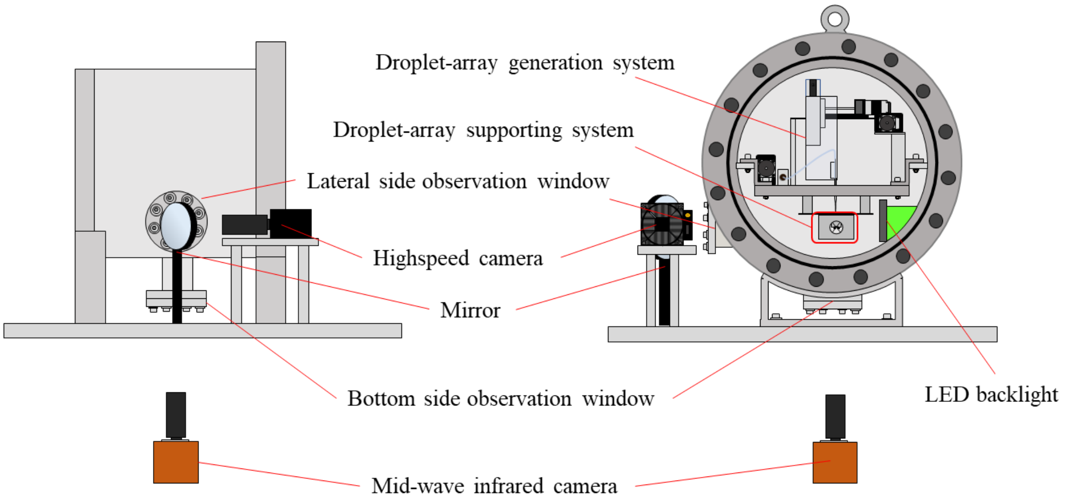
Figure 1 (a) shows a droplet-array model used in this experiment. It consists of three *n*-decane droplets. The left one is used for ignition and the other two are used for observation of flame spread. As shown in Fig. 1 (b), all droplets are tethered at a cross point of X-shaped 14μm SiC fibers (NIPPON CARBON, Hi-Nicalon) that are fixed to four aluminum rods. Droplet distances are determined by S/d_0, where the distance S between droplets is normalized by the initial droplet diameter d_0. The droplet-array-generation system consists of three stepping motors which move in X, Y and Z directions and makes droplets at any position. The droplet diameter is also controlled by a stepping motor that pushes out a plunger of a micro syringe in certain length. Figure 2 shows the initial droplet diameter of Droplet 2 and dimensionless inter droplet distance between Droplets 1 and 2. We supposed d_0 of about 0.45 mm and observed the condition near the flame-spread limit. We ignore the flame spread behavior between Droplets I and 1 because that would be disturbed by a thermal effect of hot-wire igniter.

To ignite droplets, we used half-loop shaped Fe-Cr wire electronically heated in a short time as shown in Figs. 1 (a) and (b). For observation, we used a two-way simultaneous shooting system with a high-speed camera (IDT, CCM3510) placed near the lateral-side observation window and a mid-wave infrared camera (NIT, TACHYON) placed under the bottom-side observation window as shown in Fig. 1 (c). Microgravity was realized by dropping the experimental apparatus freely in the drop experiment facility of Yamaguchi University, which has about 4.5 m height and gives microgravity of 0.95 s.



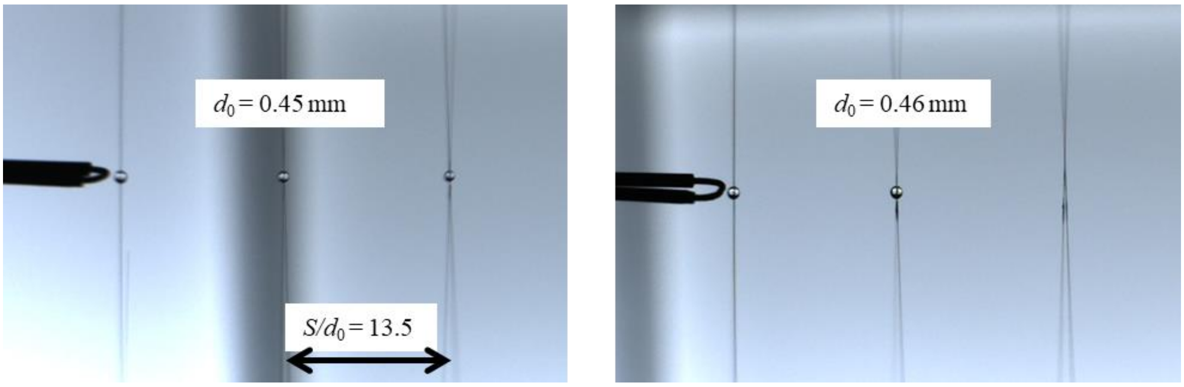
(a) Droplet-array

(b) Droplet-array supporting system



(c) Two-way simultaneous shooting system with high-speed camera and mid-wave infrared camera

Fig. 1 Experimental apparatus

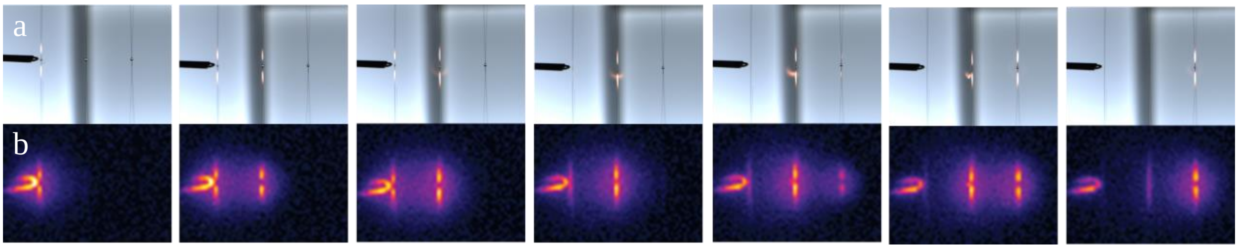


(a) with Droplet 2 (b) without Droplet 2

Fig. 2 Droplet-arrays with and without Droplet 2

3. Results and Discussion

Figure 3 shows sequential images of the flame spread behavior between Droplets 1 and 2, taken by a high-speed camera with a back-illumination displayed in Fig. 3 (a) and by a mid-wave infrared camera displayed in Fig. 3 (b). We defined $t = 0$ s/mm^2 as the moment of Droplet I ignition. Comparing the two types of images, the area of infrared luminescence is much larger than that of the diffusion flame because the former includes infrared emission from all combustion products surrounding the diffusion flame while the latter includes visible light emission from soot inside the diffusion flame. Droplet 1 ignites around 1.0 s/mm^2, then the flame spreads toward Droplet 2, and Droplet 2 ignites around 1.69 s/mm^2 with a hot flame. At 1.66 s/mm^2, Droplet 2 is not ignited yet but a weak infrared luminescence appears around the SiC fibers tethering Droplet 2 and another weak infrared luminance appears between the infrared luminance surrounding the diffusion flame of Droplet 1 and unburned Droplet 2. When 1.69 s/mm^2 ~ 2.20 s/mm^2, the luminance from the diffusion flame of Droplet 1 becomes weaker. Figure 4 shows the flame-spread behavior without Droplet 2. As in the case in Fig. 3 (b), a weak infrared luminescence appears around SiC fibers tethering Droplet 2 after 1.66 s/mm^2. This is because the SiC fibers are heated by the diffusion flame of Droplet 1. Comparison of Figs. 3 (b) and 4 (b) suggests that another weak infrared luminance appearing between the infrared luminance surrounding the diffusion flame of Droplet 1 and unburned Droplet 2 exists only with Droplet 2 and thus conceivably comes from a cool flame.



0.87 s/mm^2 1.00 s/mm^2 1.34 s/mm^2 1.66 s/mm^2 1.69 s/mm^2 1.88 s/mm^2 2.20 s/mm^2

Fig. 3. Flame-spread behavior from Droplet I to Droplet 2,

(a) high-speed camera, (b) mid-wave infrared camera

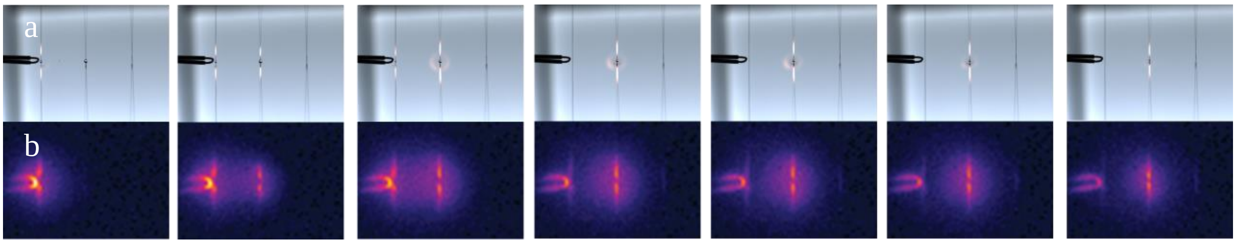


Fig.4. Combustion behavior without Droplet 2,

(a) high-speed camera, (b) mid-wave infrared camera

4. Conclusions

This study investigated the mode of flame spread including the appearance of cool flame. The conclusions of this study are as follows.

1. A cool flame appeared before the appearance of a hot flame in so-called Mode 3 flame spread.
2. The cool flame appeared between a diffusion flame and an unburned droplet heated by the diffusion flame.

References

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