JASMAC
Conference of the Japan Society of
Microgravity Application

OR2-6

微小重力高圧環境下での液滴間燃え広がりにおける冷炎を伴う液滴蒸発の調査

Study on the droplet vaporization with a cool flame in flame spread over droplets at high pressure in microgravity

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1. Introduction

Droplet combustion has been researched from a fundamental view to elucidate the mechanism of spray combustion, and flame spread over fuel droplets has been researched in microgravity, using simplified droplet systems, such as droplet arrays, droplet-cloud elements and randomly distributed droplet clouds.

In combustion of hydrocarbon fuels, low-temperature combustion called “cool flame” appears not only in premixed combustion but also in droplet combustion. The temperature of the hot flame is 1000 K or higher, while the temperature of cool flame is 580-750 K for premixed combustion and 650-880 K for droplet combustion 1). In addition, the cool flame emits faint light in the near-ultraviolet range (370-470 nm) and is therefore difficult to be observed with ordinary cameras. Tanabe et al. 2) reported that there are four types of droplet auto-ignition processes in droplet combustion depending on the ambient temperatures and pressures in air: Cool-flame ignition, only the cool flame appears; single-stage ignition, only the hot flame appears; two-stage ignition, the hot flame appears after the cool-flame; no-ignition. At high pressures, where many combustors are in operation, it is known that two-stage ignition occurs involving the cool flame appearance.

From 2009, droplet combustion experiments were conducted aboard the U.S. Experiment Module on the International Space Station (ISS) and it was reported that the cool flame appears even after the radiative extinction of the hot flame 1, 3-5). Nayagam et al. 5) reported that the *n*-decane droplet vaporization-rate constant with cool-flame is 0.39-0.40 $\mathrm{mm^2/s}$. In 2017, Mikami et al. 6-9) conducted droplet-cloud combustion experiments, “Group Combustion”, aboard the Japanese Experimental Module “Kibo” on the ISS, and suggested that a cool flame may appear even in flame spread over droplets, considering the droplet vaporization-rate constant. Based on this hypothesis, we further investigated the appearance of a cool flame in flame spread over *n*-decane droplets in microgravity 10-12). Although ”Group Combustion" was conducted at atmospheric pressure, but these study were conducted at higher pressures, where the appearance of cool flame is known to be more pronounced 10). We found that the cool flame appears around a droplet heated by interactive burning of two droplets in a narrow range of droplet spacing around the flame-spread limit of two interactive droplets, and the heat generated by the cool-flame overlap causes two-stage ignition, which is a transition from the cool flame to the hot flame. We identified the appearance of a cool flame using an infrared camera.

This study investigated the vaporization-rate constant during the cool-flame appearance by simultaneous shooting using a high-speed camera and an infrared camera in the flame spread over *n*-decane droplets in microgravity.

2. Experimental Apparatus and Procedures

Figure 1 shows the droplet-array model used in the experiments. Droplets were tethered at the intersection of 14-micron diameter SiC fibers. The droplet spacings between Droplets B and A, Droplets A and L_1, and Droplets A and L_2 are expressed as S_{BA}/d_0, S_{AL1}/d_0, and S_{AL2}/d_0, respectively, which are normalized by the initial droplet diameter d_0. Droplets B and A were fixed with S_{BA} = 2 mm as interactive droplets. Droplets L_1 and L_2 were placed to investigate the cool flame interaction near the flame-spread limit of two interactive droplets, Droplets B and A. The droplet spacing between Droplets L_1 and L_2 were fixed with S_{L1L2} = 2.1 mm.

The experimental apparatus consists of a droplet-array generator, droplet supporting system, and ignition system as shown in Fig. 2. Droplets were generated by moving a fine glass tube to an arbitrary position using a three-axis traverse stage and pushing out a predetermined amount from the micro-syringe with *n*-decane. The initial droplet diameter was d_0 = 0.4 or 0.5 mm. For the ignition of Droplet B, we used the hot wire ignition method in which a half-loop shape Fe-Cr wire with a wire diameter of 0.23 mm is electrically heated.

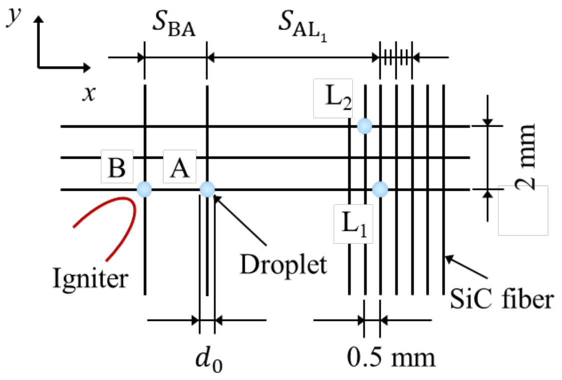


Fig. 1 Droplet-array model.

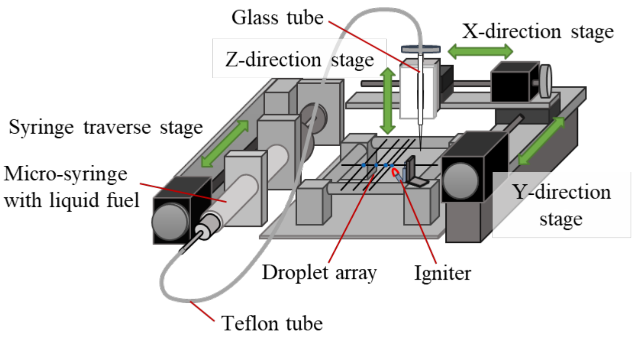


Fig. 2 Droplet-array generation system.

The microgravity experiments were conducted at a drop experiment facility of Yamaguchi University. The falling distance is 4.5 m and the microgravity duration is about 0.9 s. The experiments were conducted at room temperature in a pressure vessel pressurized with dry air to the specified pressures of 0.3 and 0.4 MPa.

In this experiment, a simultaneous shooting method using a high-speed camera (IDT, CCM3510) with 1000 fps and an infrared camera (Allied Vision, Goldeye G033 SWIR) with 160±10 fps was attempted in order to investigate the vaporization-rate constant during the cool flame appearance. As shown in Fig. 3, visible light (400-785 nm) and infrared light (825-1300 nm) were branched using a dichroic mirror (THORLABS, DMLP805L). In previous studies 10-12), the Thin Filament Pyrometry (TFP) method using an infrared camera was used to identify the appearance of cool flame by measuring the temperature of SiC fibers around the droplets. However, since TFP calibration cannot be performed accurately due to the effect of multiple reflections by the dichroic mirror in this experiment, we only determined whether a cool flame appeared or not using the infrared camera.

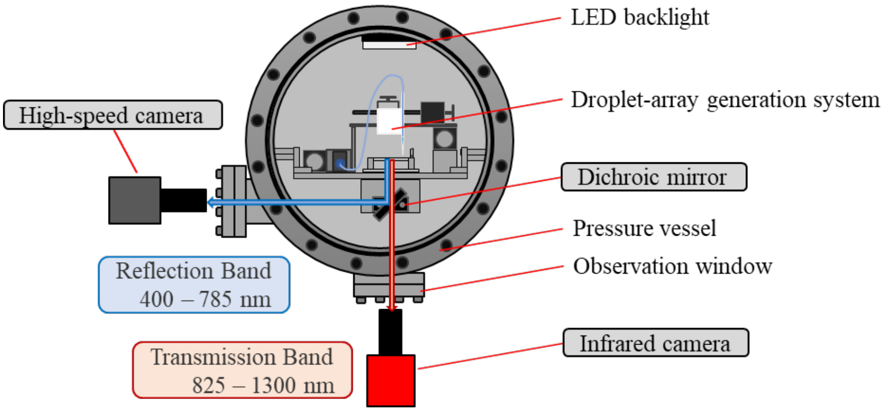


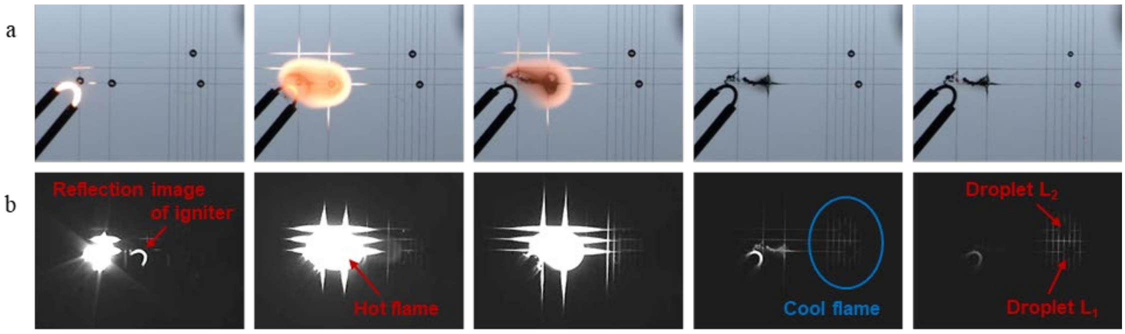
Fig. 3 Outline of simultaneous shooting system.

3. Results and Discussion

Figure 4 shows the flame-spread behavior when Droplets $\mathrm{L_1}$ and $\mathrm{L_2}$ are placed at $S_{\mathrm{AL1}}/d_0 = 12$ and $S_{\mathrm{AL2}}/d_0 = 11.7$ at 0.3 MPa. The initial droplet diameter is 0.5 mm. The starting point of the flame-spread time, 0 s, is the moment when the sensor detects microgravity. As shown in Fig. 4a, the droplet diameter decreases even though there was no hot-flame around Droplets $\mathrm{L_1}$ and $\mathrm{L_2}$ (0.70-0.90 s) after the interactive burning of Droplets B and A. As shown in Fig. 4b, the SiC fibers around Droplet $\mathrm{L_1}$ and $\mathrm{L_2}$ continued to emit faint light while the droplet diameter is decreasing, which indicates that the cool flame appeared. From a previous study 12), the temperature around Droplets $\mathrm{L_1}$ and $\mathrm{L_2}$ is estimated to be about 800 K at 0.75 mm away from the center of Droplets $\mathrm{L_1}$ and $\mathrm{L_2}$ in the x-direction, respectively, and about 860 K between the two droplets. The cool flame emits light in the near-ultraviolet range, therefor it is not able to capture by the high-speed camera, which is a visible-light camera.

Figure 5 shows temporal variations of the squared Droplets $\mathrm{L_1}$ and $\mathrm{L_2}$ diameter from 0.2 s after the sensor detected microgravity. We show approximate lines as dashed lines while Droplets $\mathrm{L_1}$ and $\mathrm{L_2}$ gets a decrease in diameter, and the equation of each approximate line is shown in the figure. We calculated the absolute value of the slope of the approximate line as the vaporization-rate constant.

As shown in Fig. 5, the droplet diameter of Droplet $\mathrm{L_2}$ decreases first, which is closer to the interactive droplets, and the vaporization-rate constant of Droplets $\mathrm{L_1}$ and $\mathrm{L_2}$ are 0.43 mm^2/s and 0.45 mm^2/s, respectively. This vaporization-rate constant is close to that with the cool flame as reported by Nayagam et al. 5) for burning 4 mm single n-decane droplet at 0.1 MPa. On the other hand, it is larger than the vaporization-rate constant of 0.31 mm^2/s reported by Mikami et al. 8-9), suggesting the appearance of cool flame in flame spread over n-decane droplets. This experiment was conducted at a high-pressure side where the appearance of cool flame strongly appears, therefore the temperature around Droplets $\mathrm{L_1}$ and $\mathrm{L_2}$ increased, and as a result, the vaporization-rate constant increased due to the decrease in the latent heat of vaporization and the increase in the surface area by the expansion of the droplets.



0.10 s　0.20 s　0.50 s　0.70 s　0.90 s

Fig. 4 Flame-spread behavior for $S_{\mathrm{AL1}}/d_0 = 12$ and $S_{\mathrm{AL2}}/d_0 = 11.7$ ($d_0 = 0.5$ mm) at 0.3 MPa.
a: high-speed camera. b: infrared camera (brightness level corrected).

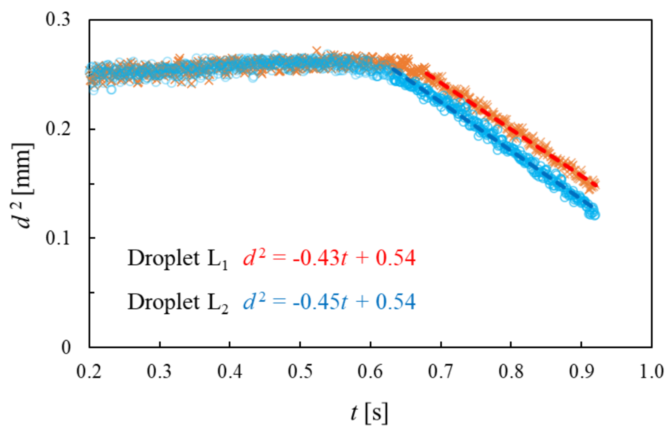


Fig. 5 Temporal variations of the squared diameter of Droplets $\mathrm{L_1}$ and $\mathrm{L_2}$.

4. Conclusions

This study investigated the vaporization-rate constant during the cool flame appearance by simultaneous shooting using a high-speed camera and an infrared camera in the flame spread over *n*-decane droplets at high pressure in microgravity. When the initial droplet diameter is 0.5 mm, the vaporization-rate constant with the cool-flame is 0.41-0.45 mm^2/s, which is slightly larger than that at atmospheric pressure.

Acknowledgements

This research was subsidized by JSPS KAKENHI Grant-in-Aid for Scientific Research (B) (18H01625 and 21H01532). The authors wish to thank Mr. Matsuura for his help in microgravity experiment.

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