JASMAC
Conference of the Japan Society of
Microgravity Appllication

P01

微小重力場を利用した異なる雰囲気圧力での正デカン液滴間燃え広がりにおける冷炎発生の調査

Study on the Appearance of Cool Flame in Flame Spread over *n*-decane Droplets at Different Pressures in Microgravity

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1. Introduction

As fundamental researches for clarifying the mechanism of spray combustion, 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. Hydrocarbon fuels used in many spray combustors are known to show low-temperature burning phenomenon called "cool flame" at 580-750 K in premixed burning in case of more than three carbons in fuel [1-2]. Tanabe et al. [3] experimentally researched the ignition process of single droplets at different ambient temperatures and pressures in air and showed that the cool flame appears even in droplet ignition and there are four types of droplet auto-ignition processes: 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 appearance; no-ignition. The ignition modes of *n*-decane droplet at different ambient temperatures and pressures is shown in Fig. 1 [4]. The temperature of the cool flame in droplet-burning is 650-880 K [2]. Mikami et al. [5-8] conducted droplet-cloud combustion experiments titled “Elucidation of Flame Spread and Group Combustion Excitation Mechanism of Randomly Distributed Droplet Clouds (Group Combustion)” in the Japanese Experimental Module “Kibo” aboard the International Space Station (ISS) and suggested that the cool flame appear in flame spread over droplets [7-8].

This study experimentally investigated whether a cool flame could appear in flame spread over fuel droplets in microgravity by varying the ambient pressure from atmospheric pressure, where only a cool flame appears in *n*-decane droplet auto-ignition, to pressures where two-stage auto-ignition occurs [4].

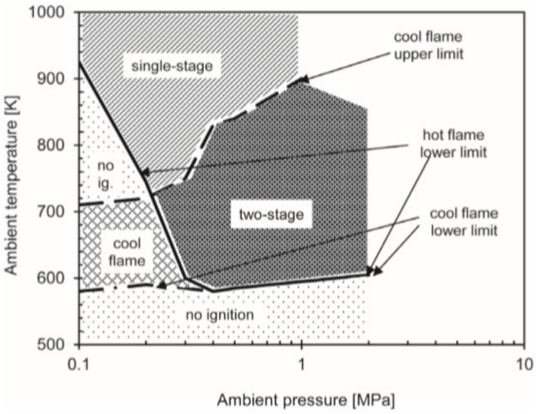


Fig. 1 Ignition-mode classification of isolated fuel droplet (fuel: *n*-decane, d_0 = 0.7 mm, in normal gravity) [4].

2. Experimental Apparatus and Procedures

Figure 2 shows the droplet-array model used in the experiments. Droplets B, A and L were tethered in a straight line at the intersection of 14-micron diameter SiC fibers. The droplet spacings between Droplets B and A, and Droplets A and L are expressed as S_{BA}/d_0 and S_{AL}/d_0, respectively, where the droplet spacing is normalized by the initial droplet diameter d_0. Droplets B and A are interactive droplets with S_{BA} = 2 mm. The droplet spacing between Droplets A and L were varied to observe the ignition behavior during flame spread over droplets. Droplet B was used as the ignition droplet due to the limited microgravity duration.

The experimental apparatus consists of a droplet-array generator, droplet supporting system and ignition system as shown in Fig. 3. 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 = 0.5 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 0.29 mm is electrically heated.

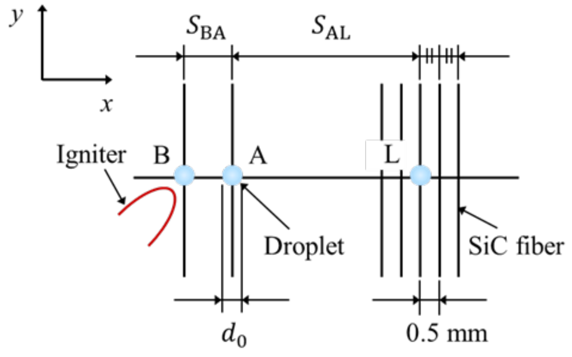


Fig. 2 Droplet-array model.

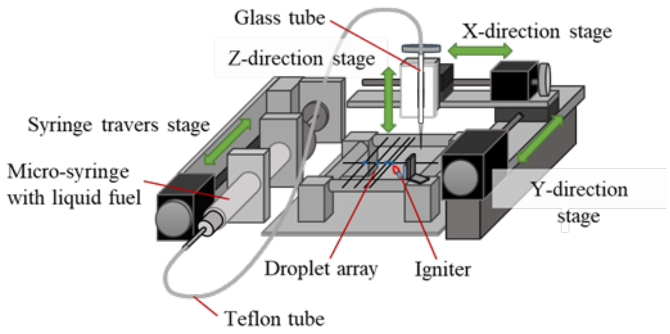


Fig. 3 Droplet-array generation system.

The microgravity experiments were conducted at a drop experiment facility of Yamaguchi University. In order to suppress the air drag to the experimental apparatus, we used a drag shield surrounding the apparatus, which drops without contact with the drag shield. The falling distance is 4.5 m and the microgravity duration is about 0.9 s. Flame spread was observed through a window of the pressure vessel by using an infrared camera (Allied Vision, Goldeye G033 SWIR) with 160±10 fps. All experiments were conducted at room temperature. When experimenting at high pressure, the pressure vessel was pressurized with dry air to prescribed pressure.

In order to identify a cool flame around Droplet L, we monitored the temperature around Droplet L near the flame-spread limit. The temperature around the droplet was measured by the Thin Filament Pyrometry (TFP) method based on the luminosity of SiC fibers. Therefore, a few SiC fibers are placed around Droplet L to confirm the temperature distribution associated with the cool-flame appearance, as shown in Fig. 2. TFP was calibrated using an infrared camera and a SiC fiber in a high-temperature furnace. The calibration range is from 664 K to 850 K (Fig. 4).

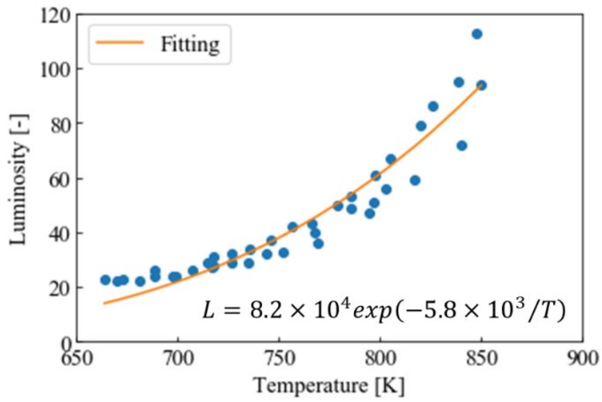
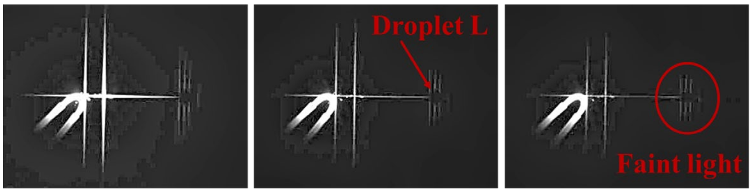


Fig. 4 Calibration result of relation between temperature and luminosity of SiC fiber using an infrared camera.

3. Results and Discussion

3.1 Atmospheric pressure environment

Figure 5 shows the flame spread behavior at 0.1 MPa when Droplet L is placed at $S_{AL}/d_0 = 17$. The starting point of the elapsed time (0 s/mm^2) is the moment when the Droplet A is just enveloped with a flame. The elapsed time is normalized by d_0^2. The SiC fibers around Droplet L continued to emit faint light at 2.09 s/mm^2, even though the thermal effect of interactive burning of Droplets B and A disappeared. Since the temperature around Droplet L is estimated to be about 730 K by the TFP method, a cool flame is considered to appear around Droplet L. At $S_{AL}/d_0 = 16$, a hot flame appeared around Droplet L and flame spread over droplets occurred, and the cool flame did not appear for $S_{AL}/d_0 = 18$. The results show that the cool flame appears in a narrow range of droplet spacing around the flame-spread limit of two interactive droplets.



t/d_0^2=1.68 s/mm^2 t/d_0^2=1.90 s/mm^2 t/d_0^2=2.09 s/mm^2

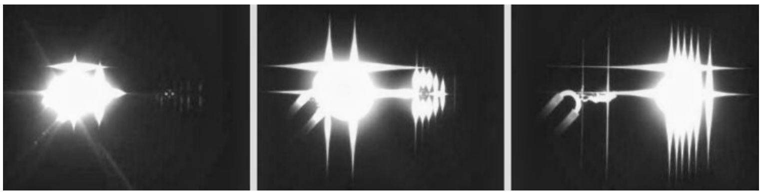
Fig. 5 Flame-spread behavior for S_{AL}/d_0=17 at 0.1 MPa (brightness level corrected).

3.2 High pressure environment

The appearance of the cool flame was more pronounced at high pressure than at atmospheric pressure. Figure 6 shows the flame spread behavior at 0.3 MPa when Droplet L is placed at $S_{AL}/d_0 = 11$, 12 and 13. As shown in Fig. 6(a), a hot flame appeared around Droplet L for $S_{AL}/d_0 = 11$. As shown in Figs. 6(b) and 6(c), the hot flame did not appear around Droplet L for $S_{AL}/d_0 = 12$ and 13. As shown in Fig. 6(b) for $S_{AL}/d_0 = 12$, however, after extinction of the flame around Droplet A, the SiC fibers around Droplet L continued to emit faint light, while it was not observed in Fig. 6(c). The results show that a cool flame is considered to appear around Droplet L by the thermal effect in the flame spread for $S_{AL}/d_0 = 12$. The cool flame appears in a narrow range of droplet spacing around the flame-spread limit of two interactive droplets even at high pressure.

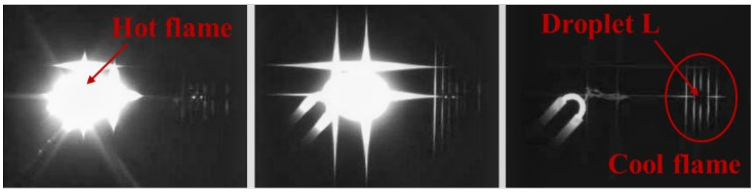
Figure 7 shows the temporal variations of temperature around Droplet L (0.75 mm away from the center of Droplet L in the x-direction) when Droplet L is placed at $S_{AL}/d_0 = 11$, 12 and 13. The temperature is calculated using TFP method from the luminosity of SiC fibers. The increase in temperature at an early stage is due to the effect of reflection of infrared light emitting from interactive burning of Droplets B and A on the SiC fibers. As shown in Fig. 6(a), Droplet L ignites with the hot flame around 1.4 s/mm^2 for $S_{AL}/d_0 = 11$, and then the flame temperature exceeds 1000 K. As shown in Fig. 7 for $S_{AL}/d_0 =$ 12 and 13, the same temperature transition trend is observed up to about 1.7 s/mm^2, but the temperature continues to fall for $S_{AL}/d_0 = 13$, suggesting that the cool flame did not appear. On the other hand for $S_{AL}/d_0 = 12$, the temperature rose again and reached about 820 K, suggesting that the cool flame appeared.

The cool flame was not observed at 0.5MPa in this experiment. The hot flame appeared around Droplet L for $S_{AL}/d_0 = 10$, and the cool flame did not appear for $S_{AL}/d_0 = 11$. Uneyama 9) reported when the ambient pressure is 0.5 MPa, a slight flow is induced in a flammable gaseous layer surrounding a droplet by Marangoni convection on the droplet surface, which affects flame spread over fuel droplets. Therefore, more detailed research is necessary on the cool flame during flame spread over droplets at 0.5 MPa and above.



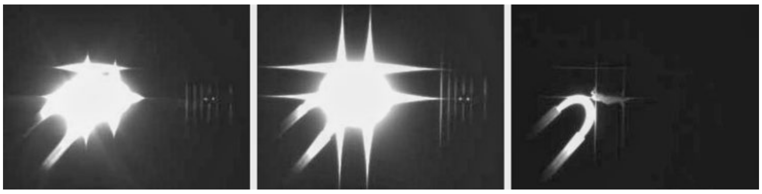
t/d_0^2=0 s/mm^2 t/d_0^2=1.39 s/mm^2 t/d_0^2=2.69 s/mm^2

(a) S_{AL}/d_0=11



t/d_0^2=0 s/mm^2 t/d_0^2=1.49 s/mm^2 t/d_0^2=2.70 s/mm^2

(b) S_{AL}/d_0=12



t/d_0^2=0 s/mm^2 t/d_0^2=1.50 s/mm^2 t/d_0^2=2.70 s/mm^2

(c) S_{AL}/d_0=13

Fig. 6 Flame-spread behavior for different S_{AL}/d_0 at 0.3 MPa (brightness level corrected).

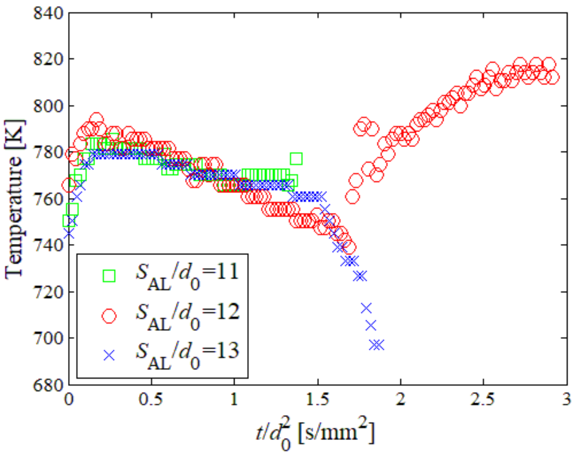


Fig. 7 Temporal variations of temperature around Droplet L for different S_{AL}/d_0 at 0.3 MPa.

4. Conclusions

This study experimentally investigated whether a cool flame could appear in flame spread over fuel droplets by varying the ambient pressure from atmospheric pressure, where only a cool flame appears in *n*-decane droplet auto-ignition, to 0.3 and 0.5 MPa, where two-stage auto-ignition occurs. The main conclusions are as follows:

(1) The cool flame appears at atmospheric pressure and 0.3 MPa. The appearance of cool flame is more pronounced at 0.3 MPa than at atmospheric pressure.

(2) The cool flame appears in a narrow range of droplet spacing around the flame-spread limit of two interactive droplets.

Acknowledgement

This research was subsidized by JSPS KAKENHI Grant-in-Aid for Scientific Research (B) (18H01625).

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