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微小重力場における冷炎を考慮した液滴間の燃え広がりに関する研究

Study on the flame spreading between droplets considering the cool flame in microgravity

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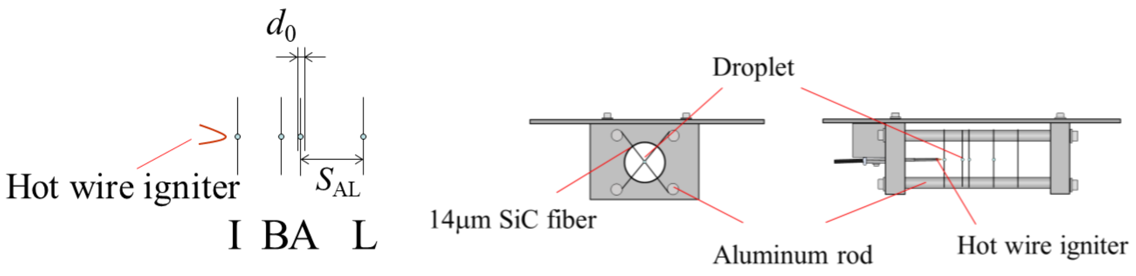
1. Introduction

Spray combustion is often used for practical combustors such as 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. Elucidation of the mechanism will contribute to higher combustion efficiency and accurate simulations. In order to research spray combustion from a fundamental viewpoint, fuel droplet arrays with a diameter of several hundred μm are often used so as to obtain enough spatial and temporal resolutions. With such droplet diameters, however, it is difficult to get rid of the effect of natural convection in normal gravity, and therefore combustion experiments are conducted in microgravity. For example, Mikami et al.1) investigated the appearance of cool flame in flame spread over droplet-cloud elements. They used a mid-wave infrared camera and captured infrared luminescence around droplets which is caused by combustion products of cool flame outside the flame-spread limit. Cool flame is a low temperature oxidation around 700 K occurring for hydrocarbon fuels, and researchers have paid attention to this phenomenon because it may affect combustion dynamics and efficiency. Mikami et al. 2) researched that Mode 3 flame spread appears in such limit of flame spreading. In this mode, the next droplet is ignited by heat from the diffusion fame whose leading edge does not reach the flammable-mixture layer around the next droplet. Harada et al.3) researched redefinition of the flame-spread mode considering cool flame in liner droplet arrays. They found there appears cool flame in Mode 3 flame spread and it turned to hot flame. Based on these results, this research focuses on the Mode 3 flame spread and researched the effect of inter-droplet distance.

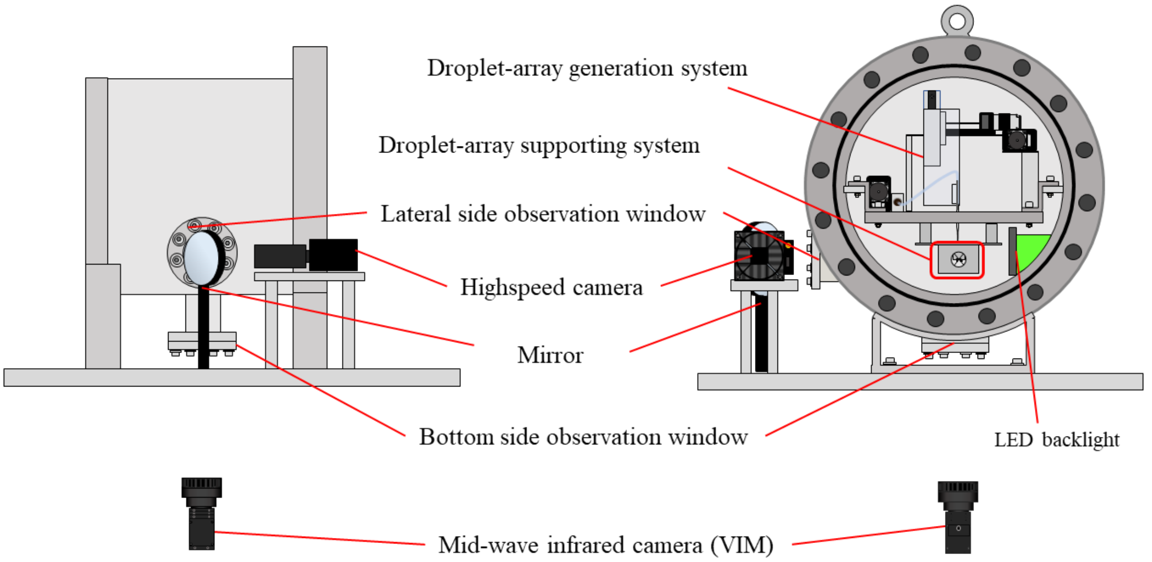
2. Experimental Apparatus and Analysis Method

This study used a droplet array model with two droplet interaction as shown in Fig. 1 (a). It consists of one ignition droplet, one interaction part: Droplets B and A, and one observation droplet: Droplet L. All droplets are tethered at cross points of X-shaped 14 μm SiC fibers (NIPPON CARBON, Hi-Nicalon) that are fixed to four aluminum rods as shown in Fig. 1(b). Inter-droplet distances are determined by S/d_0, where the distance S between droplets is normalized by the initial droplet diameter d_0. Droplet-array-generation system consisting of three stepping motors which can move in X, Y and Z directions enables us to make droplets at any position. For the droplet ignition, we used half-loop shaped Fe-Cr wire electrically heated in a short time. For observation, we used two types of cameras: a high-speed camera (IDT, CCM3510) placed near the lateral side observation window and a mid-wave infrared camera (Vision Sensing, VIM-640ULC-WB) placed near the bottom side observation window. These cameras are included in a two-way simultaneous shooting system as shown in Fig. 1 (c). When the cool flame appears, very weak infrared luminescence is emitted from the combustion products, CO_2 and H_2O. They can be observed through the mid-wave infrared camera. By comparing the mid-wave infrared image and high-speed camera image with a back-illumination, we can distinguish the hot flame and the cool flame. The experiments were conducted in room temperature and ambient pressure and used *n*-decane as a fuel. Microgravity was realized by dropping the experimental apparatus freely in the drop experiment facility of Yamaguchi University.



(a) Droplet-array model

(b) Droplet-array supporting system



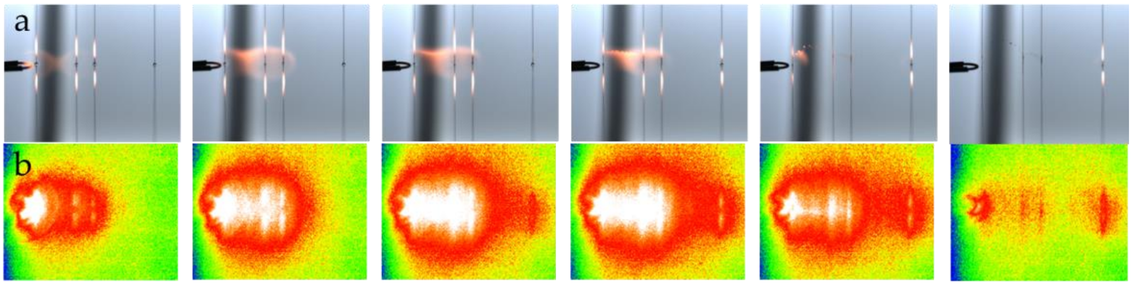
(c) Two-way simultaneous shooting system with high-speed camera and mid-wave infrared camera

Fig. 1 Experimental apparatus

3. Results and Discussion

Figure.3 shows the flame-spread behavior in $S_{BL}/d_{L0} = 15.0$, with and without flame spreading. Pictures grouped "a" were taken by the high-speed camera and those of grouped "b" were taken by the mid-wave infrared camera. Comparing from the two kinds of pictures, the infrared luminescence appears in larger area than the visible luminescence from soot of diffusion flame. In flame spreading result, the interactive two droplets, Droplets B and A, were ignited around 0.5 s/mm² and Droplet L was heated by heat from diffusion flame of the interactive droplets. At 1.26 s/mm², infrared luminescence appeared around Droplet L. After that, diffusion flame appeared at 1.51 s/mm² accompanied with strong luminescence of SiC fiber around Droplet L. Therefore, these results indicate that Mode 3 flame spread appeared. On the other hand, in the no-flame-spreading result, Droplet L was not ignited although the infrared luminescence reached near Droplet L. Under $S/d_0 = 15.0$ condition, there appeared dispersion of data: both flame-spreading and no-flame-spreading results appeared, therefore we conclude that this condition represents the flame-spread limit.

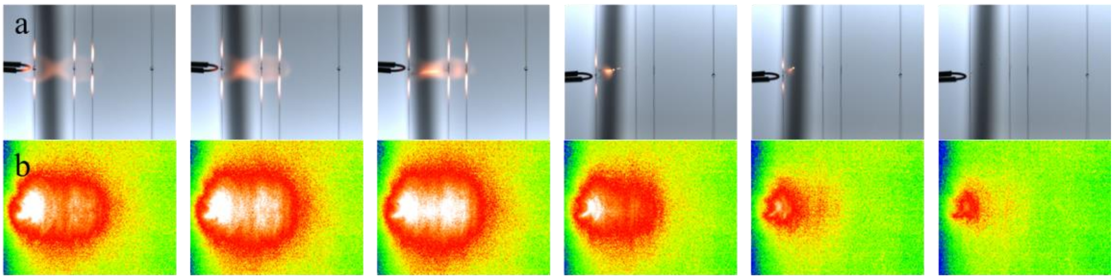
To know the detail of the result in Fig. 3(b), we analyzed the distribution of luminescence value for flame spreading direction as shown in the plots in Fig. 4. The vertical axis shows the infrared luminescence value that reflects the average of 12 pixels in droplet center and the horizontal axis shows the distance from Droplet L normalized by its initial diameter. When diffusion flame appeared around the interactive droplets, there were some peaks around 2400. After that at 1.26 s/mm^2, another peak appeared around Droplet L and had smaller luminescence value than the diffusion flame of interactive droplets. When Droplet L was ignited, the peak value was increased. Comparing the result of Fig. 2 (a) and (b) at 1.26 s/mm^2, the high-speed camera image doesn't include any phenomenon around Droplet L. On the other hand, infrared luminescence appears around Droplet L in the infrared image. Furthermore, in Fig. 4 at 1.26 s/mm^2 the infrared luminescence appeared around Droplet L has smaller peak than diffusion flame appeared at 1.51 s/mm^2. Therefore, the luminescence comes from the cool flame.



0.50 s/mm^2 1.00 s/mm^2 1.26 s/mm^2 1.51 s/mm^2 1.76 s/mm^2 2.01 s/mm^2

Fig. 2 Burning behavior with flame spreading to Droplet L

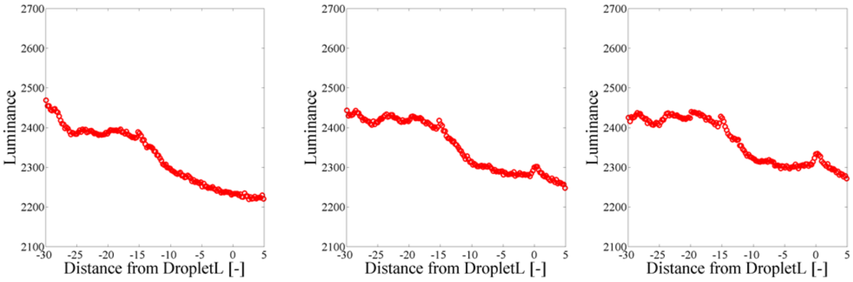
(a) high-speed camera (b) mid-wave infrared camera



0.58 s/mm^2 0.87 s/mm^2 1.16 s/mm^2 1.45 s/mm^2 1.74 s/mm^2 2.03 s/mm^2

Fig. 3 Burning behavior without flame spreading to Droplet L

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



1.00 s/mm^2 1.26 s/mm^2 1.51 s/mm^2

Fig. 4 Luminescence distribution at different times in the same condition as in Fig. 2 (b)

4. Conclusion

This study investigated flame spread behavior near the flame-spread limit considering the appearance of cool flame. The conclusions of this study are as follows.

1. Cool flame was observed in the flame spread over unevenly arranged droplet array consisting of Droplets I, B, A and L. The infrared luminescence distributed around Droplet L.
2. Cool flame has a smaller luminescence peak than diffusion flame.

5. Acknowledgements

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6. References

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