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Flame spread between two droplets of different diameter in microgravity

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ABSTRACT

This research investigates the flame-spread characteristics between two droplets, Droplets A and L, of different diameter. *n*-Decane droplets are placed at intersections of 14 μ SiC fibers. The flame spread from Droplet A to Droplet L was observed in microgravity. The results show that the flame-spread rate decreases with an increase in the droplet spacing or the initial diameter of Droplet L for a constant initial diameter of Droplet A. The flame-spread time is approximated as the summation of the thermal conduction time from the flame around Droplet A to Droplet L and the heating time of Droplet L, which is the time required to activate the vaporization of Droplet L. Both the thermal conduction time and the heating time of Droplet L increase with the droplet spacing. The latter also linearly increases with the squared initial droplet diameter of Droplet L. The results suggest that the ratio of the heating time of Droplet L to the thermal conduction time depends roughly on the droplet diameter of Droplet L alone for a constant initial diameter of Droplet A. The flame-spread-limit droplet spacing gradually decreases with an increase in the initial droplet diameter of Droplet L and increases sharply with the initial droplet diameter of Droplet A. The flame-spread time is limited by the burning lifetime of Droplet A and about 80% of the burning lifetime of Droplet A under the near-flame-spread-limit condition. The flame-spread limit is discussed considering the burning lifetime of Droplet A, the thermal conduction time, and the heating time of Droplet L.

1. Introduction

Liquid-fueled combustors employ spray combustion, which is a complicated form of combustion because fuel droplets of different sizes are dispersed randomly, and many processes, such as liquid–fuel atomization, droplet vaporization, chemical reaction, occur simultaneously. Combustion of a small number of droplets in microgravity has been studied in fundamental research, e.g., single-droplet or two-droplet combustion, since the pioneering work by Kumagai and Isoda [1]. Recently, many researchers have extensively investigated flame spread along fuel droplet arrays in microgravity experimentally [2–8], numerically [11–12], and theoretically [9–10].

Mikami et al. [13] experimentally studied the burning behavior of premixed sprays in a counterflow burner using *n*-decane and discussed the flame structure and stabilization based on the flame-spread mechanism of the droplet array with a low-volatility fuel and flame-spread data in microgravity. Although the droplets in real sprays are randomly distributed and have a size distribution, such effects on the flame spread were not considered in the discussion. Some researchers developed percolation models that are based on findings from microgravity flame-spread experiments and predict the group combustion excitation of fuel sprays through flame spreading over randomly distributed droplet clouds [7,14,15]. Oyagi et al. [7] experimentally investigated the flame-spread-limit distance of unequally spaced droplet arrays in microgravity and showed that the flame-spread-limit distance increases with droplet interaction. They considered the local interactive effect on the flame spread in the percolation model. Recently, Mikami et al. [16] conducted microgravity experiments of flame spread over droplet-cloud elements to obtain the local interactive effect data applied to the percolation model with three-dimensionally distributed droplet clouds. Despite such efforts, flame spread over droplets of different size has not been elucidated. The steady-state burning of a small number of droplets of different droplet size has been analyzed theoretically by some researchers [17–19] but unsteady combustion of droplets of different droplet size has not been studied.

This research conducted microgravity experiments to investigate the flame-spread characteristics between two droplets, Droplets A and L, of different droplet diameter. The flame spread from Droplet A to Droplet L was observed in microgravity using

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n-decane as a fuel. The effects of both Droplets A and L are discussed in view of some elementary processes appearing in the flame spread between droplets.

2. Experimental apparatus and procedures

A droplet array model with different droplet diameters is shown in Fig. 1. We use linear droplet arrays consisting of three *n*-decane droplets, Droplets I, A and L placed at intersections of 14 µ SiC fibers (Nippon Carbon, Hi-Nicalon). Droplet I was ignited to initiate the flame spread in microgravity and the flame spread from Droplet A to Droplet L was observed. The initial droplet diameter of Droplets I, d_{I0}, was set to be same as that of Droplet A, d_{A0}. The droplet spacing between Droplets I and A was $S_{IA}/d_{A0} = 10$ so that the interactive effect between Droplets I and A on the flame spread from Droplet A to Droplet L was negligible [7]. In the experiments to study the flame-spread rate, we used $d_{A0} = 0.7$ mm in most cases, $d_{A0} = 0.5$ mm for $d_{L0}/d_{A0} = 2$ and $d_{A0} = 0.35$ mm for $d_{L0}/d_{A0} = 3$, where d_{L0} is the initial droplet diameter of Droplet L. In the experiments to study the flame-spread limit, we used $d_{A0} = 0.35$ mm for $d_{L0}/d_{A0} = 3$ and $d_{A0} = 0.5$ mm in the other cases. The initial droplet diameter of Droplet L was varied so that the droplet diameter ratio d_{L0}/d_{A0} ranged from 0.5 to 3. The effect of tethering fiber on the flame spread is discussed later.

Figure 1 also shows a schematic of the experimental apparatus. Each droplet was generated at a designated cross point of 14 µm SiC fibers by supplying the fuel, *n*-decane, through a glass needle whose inner diameter was about 40 µm. The fuel was fed from a stepping-motor-driven micro-syringe to the glass needle through a Teflon tube. The initial droplet diameter was controlled by a stepping motor pulse with an uncertainty of 2.4%. The position of the glass needle tip was controlled by a three-axis traverse system [16]. After generating all the droplets, a digital video camera (SANYO, DMX-FH11) was moved over the droplets to start recording the initial droplets and the flame-spread behavior. The frame rate of the video camera was 240 fps. Droplet I was ignited by a hot-wire igniter in microgravity. The microgravity experiments were performed at the drop facility of Yamaguchi University, Japan. The microgravity duration is 0.95 s. All the experiments were performed at atmospheric pressure and at room temperature. Since the boiling point of *n*-decane at atmospheric pressure is 447 K, the pre-vaporization of the droplets from the start of droplet array generation until the ignition is negligible in room-temperature air.

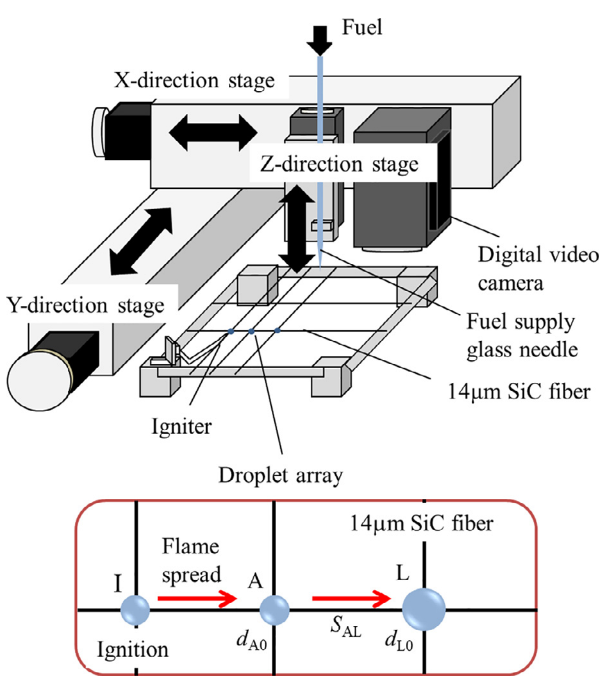

Fig. 1. Droplet-array model for flame spread from Droplets A and L of different diameter and apparatus for flame-spread experiment. Droplet I is the droplet for ignition of the droplet array.

3. Results and discussion

3.1. Results of flame-spread rate and flame-spread limit

Figure 2 displays direct images of the flame-spread behavior from Droplet A to Droplet L with $S_{AL}/d_{A0} = 6$ for different droplet diameter ratios d_{L0}/d_{A0}. The initial droplet diameter of Droplet A was $d_{A0} = 0.7$ mm. Time t starts from the moment of ignition of Droplet A. The third image was taken one frame after the ignition of Droplet L. A bright blue flame is seen around Droplet L right after the Droplet L ignition for $d_{L0}/d_{A0} = 0.5$. The flames around Droplet L $d_{L0}/d_{A0} = 1.0$ and 1.5, however, are not so clear as for $d_{L0}/d_{A0} = 0.5$. The light emission from the fibers around Droplet L suggests that there is a flame around Droplet L since the fiber emission is visible at a temperature higher than 1000 K in this system [16]. The ignition time of each droplet is defined as the first appearance of a blue flame around each droplet. Even for lager diameter of Droplet L shown in Fig. 2, a blue flame exists although it is dim and not clear. In such cases, we enhanced the brightness of the image and checked if the blue flame appeared or not. As can be seen in Fig. 2, it takes longer for the flame to spread to Droplet L for larger d_{L0}.

Figure 3 displays direct images of the flame-spread behavior from Droplet A to Droplet L with $S_{AL}/d_{A0} = 12$ for different droplet diameter ratios d_{L0}/d_{A0}. The initial droplet diameter of Droplet A was 0.7 mm. Similar to the cases with $S_{AL}/d_{A0} = 6$ shown in Fig. 2, the flame-spread time from Droplet A to Droplet L is longer for larger d_{L0}. It is, however, much longer than that with $S_{AL}/d_{A0} = 6$. Since the leading edge of the fiber emission in the outer region of the flame around Droplet A extends over time in the direction of Droplet L, the thermal layer develops from Droplet A to Droplet L over time.

The dependences of the flame-spread rate on droplet spacing for different droplet diameter ratios are shown in Fig. 4. The flame-spread rate V_f was obtained as $V_f = S_{AL}/t_{fAL}$, where S_{AL} is the droplet spacing between the centers of Droplets A and L, and t_{fAL} is the flame-spread time, which is the time required from the

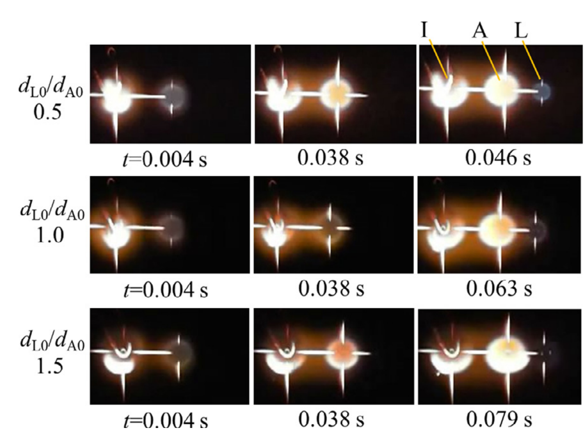

Fig. 2. Flame-spread behavior from Droplet A to Droplet L with $S_{AL}/d_{A0} = 6$ for different droplet diameter ratios d_{L0}/d_{A0}. $d_{A0} = 0.7$ mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)