Droplet Array Combustion Experiments on Effect of Initial Droplet Diameter on Flame Spread Characteristic Time*  

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Fuel droplet array combustion experiments of a fuel droplet array were performed at microgravity to investigate the mechanism of fuel droplet group combustion. The purpose of this research is to understand the dependence of flame spread speed on droplet spacing and initial droplet diameter. Ten fuel droplets were generated using a thin glass needle and suspended at the crossing points with SiC fibers of 7.5 and 14 µm in diameter, respectively. Sequential backlit-images of the droplet suspension fibers and the droplets were taken at the time of flame spread. n-Decane was employed as the fuel. The effect of initial droplet diameter on the normalized flame spread speed were examined with varying droplet spacing. In the case of 3.75 in nondimensional droplet spacing showed that the normalized flame spread speed increased less than 0.48 mm in initial droplet diameter and remained constant above 0.48 mm. In the case of short flame spread induction times, which is the time for a flame to travel between two droplets, the normalized flame spread speed increased as the initial droplet diameter increased. The reason for this believed to the flame spread induction time is dominated by the premixed-flame propagation time.  

Key Words: Spray Combustion, Initial Droplet Diameter, Fuel Droplet Array, Flame Spread Speed, Microgravity

1. Introduction  
Spray combustion is employed in various combustors, such as diesel engines, gas turbines, industrial furnaces, and liquid-fuel rocket engines. Understanding spray combustion mechanisms contributes to improving combustor performance and reducing harmful gas emissions that cause environmental pollution. Spray combustion consists of very complex aerodynamic, thermodynamic, and chemical processes. Because it is quite difficult to study these processes in detail, there are still unknown areas in spray combustion mechanisms. Researching flame spread along a fuel droplet array is an important approach to clarifying the growth mechanisms of fuel droplet group combustion. Therefore, studies of droplet array combustion have been conducted under various experimental conditions.1–18) In most past experiments of flame spread along a droplet array, the initial droplet diameter was about 1.0 mm. Improving the spatial and temporal resolution of the flame spread phenomenon would facilitate observation. Even though experimental results have been obtained for droplet arrays of large initial droplet diameters, it is possible to estimate approximate flame spread between fine fuel droplets in a real spray from the experimental results normalized by the initial droplet diameter if the chemical reaction time and radiation heat loss are negligible. However, the flame spread phenomenon progresses at high speed when the initial droplet diameter is small. In the high-speed phenomena, the ratio of chemical reaction time against the time required for the flame spread increases. To relate past studies of flame spread along a droplet array to real spray combustion, it is necessary to clarify the effects of initial droplet diameter and droplet spacing on the flame spread phenomena.  

In previous work,19) the effects of droplet spacing on flame spread induction time were studied, and the initial droplet diameter was fixed at 0.8 mm. In the present work, flame spread along a fuel droplet array was observed using various droplet spacings and initial droplet diameters. Characteristic times of each element of flame spread induction time are discussed.  

2. Experimental Apparatus and Procedure  
2.1. Experimental apparatus  
Figure 1 shows the experimental apparatus. The apparatus for microgravity experiments consisted of combustion chamber, droplet generator, fuel feed pump, droplet array slider, and droplet array suspension system. All devices were controlled by a programmable sequencer. The droplet array suspension system was equipped with one silicon carbide fiber of 7.5 µm in diameter, which was set parallel to the flame spread direction, and ten silicon carbide fibers of 14 µm in diameter (Hi-Nicalon, Nippon Carbon), which were set orthogonal to the flame spread direction. The fuel droplets were suspended at the point of intersection of two fibers. Droplet spacing was determined by the spacing of the fiber set orthogonal to the flame spread direction. The droplet array suspension system was mounted on the droplet array slider. A slider-crank mechanism driven by a stepping motor was applied to the droplet array slider. Liquid fuel was through by a glass needle, and ten droplets were quickly generated one by one. A fuel feed pump, which had a piezoelectric element, was employed to control the fuel discharge amount with high

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accuracy. The outer diameter of the fine-drawn glass needle was approximately 40 μm. The first droplet was ignited by a hot wire (iron-chrome wire of 0.39 mm in diameter), which was mounted on the droplet array suspension system holder. Two video cameras were installed in the experimental apparatus; namely, a high-speed color digital video camera (Phantom Miro 3, frame speed 2,000 fps; exposure time open; and image size 512 × 384 pixels, Vision Research Ltd.) for observing flame spread behavior, and a CCD camera (WAT-535EX, image size 768 × 494 pixels, Watec Co., Ltd.) for monitoring droplet generation and measuring the initial droplet diameter. Measurements of the premixed-flame propagation speed around a droplet were conducted with an image intensifier and a high-speed video camera (Phantom V4-i, frame speed 1,000 fps, exposure time open; and image size 256 × 256 pixels, Vision Research Ltd.).

2.2. Measurement

Initial droplet diameter was obtained from a backlit digital video of the target droplets using a self-made computer-aided image analyzer.\(^{20}\)

Ignition of the target droplet was obtained by the glowing of the 14 μm silicon carbide fibers in the droplet array suspension system. Figure 2 shows the glowing fibers heated by a flame spreading along a droplet array. The images obtained from a color digital video of the target droplets were measured using a self-made computer-aided image analyzer.\(^{19}\) When the fibers glow, the red brightness levels increase, but the blue brightness levels remain almost constant. Using this fact, the threshold value of the ratio of red brightness level and blue brightness level (RRB) was determined for droplet ignition. Ignition time was defined as the time before one frame of the first flame from which the RRB continuously exceeds the threshold value. Flame spread speed \(V_s\) was obtained from the ignition times and the droplet positions. The flame spread speed was defined as the average value after conducting the experiment three times.

Initial flame diameter was also obtained by the glowing of silicon carbide fibers of the droplet array suspension system. Because the fibers glow the brightest in at the flame, the flame position was defined as the average distance from the center of the droplet weight by RRB. The initial flame diameter was defined as the average value of the initial diameter of the flame at the 3rd–9th droplet.

2.3. Experimental conditions

The experimental conditions are listed in Table 1. \(n\)-Decane was employed as the fuel. Experiments were performed at atmospheric pressure. The droplet spacing \(S\) was varied from 0.7 to 4.38 mm. Droplet spacing was defined as the average of all center-to-center distances of the droplets. The initial droplet diameter \(d_0\) was varied from 0.35 to 0.9 mm. The initial droplet diameter \(d_0\) was defined as the average value of the initial diameter of the 3rd–9th droplets. The 1st, 2nd and 10th droplets were excluded from the calculation of average value of the initial diameter. Experiments (except the flame propagation speed measurements) were conducted in microgravity. The microgravity condition was produced by our own small drop tower (microgravity duration: 1.1 s, microgravity level: below \(10^{-4}\) \(G_0\)). The flame propagation speed measurements were conducted under normal gravity.

3. Experimental Results and Discussion

3.1. Flame spread speed

Figure 3 shows flame spread speed as a function of initial droplet diameter. The variation of each plot is less than 13%. In the case of \(S/d_0 = 2\) and 6.25, the flame spread speed increased as the initial droplet diameter decreased. The case of \(S/d_0 = 6.25\) had a higher flame spread speed dependence.
with the initial droplet diameter than $S/d_0 = 2$. In the case of $S/d_0 = 3$ and $3.75$, the flame spread speed reached the maximum value at $d_0 = 0.4 – 0.48 \text{ mm}$. Figure 4 shows the normalized flame spread speed as a function of the initial droplet diameter. Mikami et al.\(^{12}\) proposed that the flame spread speed normalized at the initial droplet diameter based on the similarity rule. To explain the dependence of the normalized flame spread speed $V/d_0$ on the normalized spacing $S/d_0$, flame spread induction time $t_f$ was used. The flame spread induction time is the time for a flame to travel between neighboring droplets, and the flame spread speed is obtained as

$$V_f = S/t_f$$  \hspace{1cm} (1)

The flame spread induction time, $t_f$, consists of the thermal conduction time of the high temperature area, $t_c$, time for activation of droplet vaporization (droplet heating time), $t_h$, time for premixed-flame propagation around the droplet, $t_p$, and the chemical ignition delay time, $t_i$.

$$t_f = t_c + t_h + t_p + t_i$$  \hspace{1cm} (2)

t_c$ is the time for heat transfer over droplet spacing $S$ by thermal conduction. It is approximately expressed as

$$t_c \approx S^2/\alpha$$  \hspace{1cm} (3)

where $\alpha$ is the thermal diffusivity of the gas. $t_h$ corresponds to the physical ignition delay. The summation of $t_h$ and the chemical ignition delay $t_i$ is the ignition delay time of the fuel droplet. The premixed-flame propagation time is

$$t_p = L/V_p$$  \hspace{1cm} (4)

where $L$ is premixed-flame path length, and $V_p$ is the flame propagation speed around droplet. If the leading edge of the initial flame does not reach the next unburnt droplet, the premixed-flame path length is

$$L = \pi d_i/2$$  \hspace{1cm} (5)

where $d_i$ is the initial flame diameter. The flame induction time was divided into these characteristic times and discussed for flame spread along arrays of the constant initial droplet diameter.

In the case of $S/d_0 = 3.75$, $d_0 \geq 0.48 \text{ mm}$ and $S/d_0 = 6.25$, the normalized flame spread speed was almost constant with the initial droplet diameter. Under these conditions, it is thought that the thermal conduction time from a spreading flame to an unburnt droplet and time until an unburnt droplet generates a flammable fuel vapor-air mixture (droplet heating time) were dominant in the flame spread between two droplets. The thermal conduction time and droplet heating time are proportional to the square of the initial droplet diameter. Therefore, the normalized flame spread speed is independent of the initial droplet diameter when the nondimensional droplet spacing is constant. In the case of $S/d_0 = 2$, $3$ and $S/d_0 = 3.75$, $d_0 \leq 0.48 \text{ mm}$, the normalized flame spread speed increased as the initial droplet diameter increases. In this condition, the characteristic times that accounts for the major part of the flame spread induction time is considered to be proportional to the square of the initial droplet diameter. The thermal conduction time and droplet heating time are proportional to the square of the initial droplet diameter. On the other hand, premixed-flame propagation around the droplet time is not proportional to the square of the initial droplet diameter. The after-mentioned results suggest that the premixed-flame propagation time increases as the initial droplet diameter decreases; as a result, normalized flame spread speed decreases. Figure 5 shows the initial stand-off ratio of the flame as a function of the initial droplet diameter at various nondimensional droplet spacings. The variation of each plot is up to $\pm 17\%$. The initial stand-off ratio of the flame increases as the initial droplet diameter decrease. The initial stand-off ratio of the flame is also independent of the droplet spacing. It was thought that the initial stand-off ratio of flame was dependent on the Damkohler number. The distance ratio from the initial flame around the droplet to next unburnt droplet decreases as the initial...
droplet diameter at the same nondimensional droplet spacings increase.

3.2. Flame spread induction time

Figure 6 shows the flame spread induction time as a function of the initial droplet diameter at various nondimensional droplet spacings. The flame spread induction time decreases as the initial droplet diameter decreases. Under the condition where the similarity rule is not true as shown in Fig. 4, the flame spread induction time shows values of less than 20 ms. Under the condition where the flame spread speed is very large, time for premixed-flame propagation around the droplet should be considered.

Measurements of the premixed-flame propagation speed around a droplet were carried out to clarify the ratio of premixed-flame propagation time to flame spread induction time. Since the premixed-flame propagation time is short, the influence of natural convection is assumed to be negligible. Figure 7 shows the premixed-flame propagation speed around the droplet as a function of the initial droplet diameter. Under the condition of $S/d_0 = 2$, the premixed-flame propagation speed was about half for $S/d_0 = 4.7$ to 5.7. It is believed that the premixed-flame propagation speed decreased due to the droplet’s cooling effect. The ratio of the premixed-flame propagation time to flame spread induction time is calculated from Figs. 4, 5 and 6. In the case of $S/d_0 = 6.25$, $d_0 = 0.7 \text{ mm}$, it is $t_f = 75 \text{ ms}$, $d_f/d_0 = 3.0$ and $V_p = 725 \text{ mm/s}$. The premixed-flame propagation time around the droplet is 4.5 ms. The ratio of the premixed-flame propagation time to the flame spread induction time is about 6%. In the same way, in the case of $S/d_0 = 2$, $d_0 = 0.9 \text{ mm}$, the premixed-flame propagation time is 9.5 ms. The ratio of the premixed-flame propagation time to the flame spread induction time is about 36%. In the latter case, the premixed-flame propagation time has a large influence on the flame spread speed. The premixed-flame propagation time becomes more dominant when the flame spread speed is large.

4. Conclusion

Flame spreading along a 10-droplet-array of $n$-decane at various droplet spacings and initial droplet diameter was investigated to understand the effects of initial droplet diameter on normalized flame spread speed and initial stand-off distance of flame. Characteristic times making up the flame induction time were discussed. Conclusions follow:

1) Depending on the nondimensional droplet spacings, the initial droplet diameter dependence of the flame spread speed differs.

2) In the case of $S/d_0 = 3.75$, $d_0 \geq 0.48 \text{ mm}$ and $S/d_0 = 6.25$, the normalized flame spread speed was almost constant with the initial droplet diameter. It is thought that the thermal conduction time from a spreading flame to an unburnt droplet and the time until an unburnt droplet generates a flammable fuel vapor-air mixture (droplet heating time) were dominant in the flame spread between two droplets.

3) In the case of $S/d_0 = 2$, $3$ and $S/d_0 = 3.75$,
$d_0 \leq 0.48 \text{ mm}$, the normalized flame spread speed increased as the initial droplet diameter increases. It is believed that the phenomenon occupying most of the flame spread induction time is proportional to the square of the initial droplet diameter.

(4) The initial stand-off ratio of flame increased as the initial droplet diameter decreases, and is almost independent of droplet spacing. It is believed that the initial stand-off ratio of flame is dependent on the Damkohler number.

(5) Under the condition that the similarity rule is not true, the flame spread induction time showed values less than 20 ms. Under the condition where the flame spread speed is very large, time for premixed-flame propagation around the droplet should be considered.

(6) The premixed-flame propagation speed when $S/d_0 = 2$ was about half of that in the $S/d_0$ range from 4.7 to 5.7. It is believed that the premixed-flame propagation speed decreased due to the droplet’s cooling effect.

(7) In the case that the flame spread induction time was short, flame spread speed was influenced by premixed-flame propagation time.

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