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微小重力場における燃え広がり限界外の液滴の可燃性混合気層形成に与える液滴間距離の影響に関する実験的調査

Experimental investigation of the effect of droplet spacing on the formation of flammable-mixture layer outside the flame-spread limit of droplets in microgravity

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Abstract: "Group Combustion" experiments were conducted using randomly disutributed fuel-droplet clouds aboard the Japanese experimental module, Kibo, on the International Space Station. These experiments suggest that multiple droplets' pre-vaporization is related to the unique combustion phenomena observed, such as large-scale ignition. The purpose of this study is to investigate how the droplet burning affects droplets outside the flame-spread limit, focusing the pre-vaporization. In this experiment, we investigated how the distance between a burning droplet, Droplet I, and an unburned droplet, Droplet A, affects the formation of a flammable-mixture layer around Droplet A, which exists outside the flame-spread limit of Droplet I, due to heat from the flame of Droplet I in microgravity. The results show that the diameter of the flammable-mixture layer increases over the pre-heating time and is smaller for the larger droplet spacing under the same pre-heating time condition.

Keywords: **Droplet array, Flammable-mixture layer, Flame-spread limit, Droplet spacing**

1. Introduction

Spray combustion is used in internal combustion engines such as diesel engines and jet engines. Spray combustion is a method of combusting liquid fuel by spraying it from a spray nozzle and atomizing it into micrometer-scale droplets. Elucidation of the mechanism of spray combustion will enable improvements in combustion efficiency and simulation accuracy. However, spray combustion involves multiple elementary processes such as droplet vaporization and chemical reactions occurring in a short time, making observation difficult. Therefore, as a fundamental study of spray combustion, droplet combustion has been widely investigated, where the droplet diameter is enlarged to the mm scale and thus the time and special resolutions are improved. When droplet diameter is enlarged to the mm-scale, however, the effect of natural convection becomes significant in normal gravity. Therefore, experiments are often conducted in microgravity to reduce the effect of natural convection. In previous studies, Mikami et al. [1] reported that the flame-spread limit between droplets using *n*-decane as a fuel in microgravity is the dimensionless droplet spacing S/d_0=14 at an ambient temperature of 300 K. In addition, Mikami et al. [2] reported that the group-combustion-excitation limit in the dimensionless mean droplet spacing is $(S/d_0)_m$ = 15.2 to 16.2 in flame-spread experiments over randomly distributed fuel-droplet clouds aboard the Japanese experiment module, Kibo, on the International Space Station. During flame-spread near the group-combustion-excitation limit, unique combustion phenomena such as large-scale ignition of droplet clusters were observed. This phenomenon is probably influenced by the pre-vaporization of multiple droplets existing outside the flame-spread limit and the generation of cool flames.

The purpose of this study is to investigate the pre-vaporization of droplets existing outside the flame-spread limit of a burning droplet and the flammable-mixture formation in microgravity. We investigated the effect of the distance between a burning droplet and an unburned droplet on the formation of a flammable-mixture layer around the unburned droplet existing outside the flame-spread limit.

2. Experimental apparatus and methods

In this experiment, a free-fall method was used to obtain a microgravity environment. Microgravity was realized by dropping the experimental apparatus freely with a drag shield in the drop-experiment facility of Yamaguchi University. The microgravity time obtained is approximately 0.9 s. A droplet-generation system was used to generate droplets of the same diameter at the intersection of 14 μm diameter SiC fibers (Nippon Carbon, Hi-Nicalon). The generation position was controlled using traverse stages that can move in three axes, and droplets were generated by pushing *n*-decane out of a fine glass tube[3)].

Figure 1 shows a droplet-array support system. As shown in Fig. 1, the droplets are supported. Two droplets were arranged as a droplet-array, with Droplet I generated as the ignition droplet and Droplet A generated as the observation droplet. Since the flammable-mixture layer cannot be observed with a high-speed camera. Therefore, Mikami et al.[4)] investigated that the flammable-mixture layer existed at the same size as the initial flame. We observed the initial flame formed by igniting the flammable-mixture layer and thus evaluated the size of flammable-mixture layer with local equivalence ratio of unity. To ignite Droplet I and the flammable-mixture layer around Droplet A, electrically heated Fe-Cr wires, Hot-wire igniters 1 and 2, were used respectively. In this case, the time required for the formation of a flammable-mixture layer was set by setting the energizing delay time for Hot-wire igniter 2 from the ignition of Droplet I to the ignition of Droplet A. These devices were installed inside a pressure vessel, and the flame-spread behavior was observed through the observation window using a high-speed camera (IDT, CCM3510) installed outside of the pressure vessel. All the experiments were conducted at room temperature and atmospheric pressure.

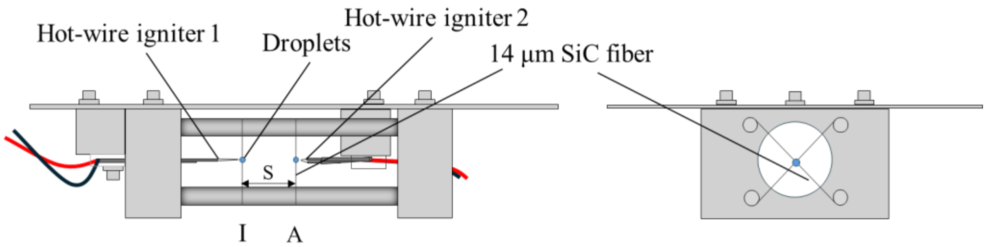

Fig. 1 Droplet-array and igniters to start flame-spread and to investigate a flammable-mixture layer

The experiments were conducted under two conditions of droplet spacing S = 7 mm and 8 mm, with an initial droplet diameter d_0 = 0.5 mm, i.e., dimensionless droplet spacings S/d_0 = 14 and S/d_0 = 16. In addition, experiments were conducted under five conditions of energizing delay time t_{ed} for Hot-wire igniter 2: 0.2 s, 0.3 s, 0.4 s, 0.5 s, and 0.6 s. The flame images captured by the high-speed camera are dark and difficult to identify the flames, we used the brightness correction function of an image processing software ImageJ[5)] to correct the images, enabling identification of the flames. We then calculated the initial flame diameter of Droplet A and examined the size and shape of the flammable-mixture layer.

3. Results and Discussion

Figures 2(a) and (b) shows the initial-flame formation when the flammable-mixture layer formed around Droplet A is ignited by Hot-wire igniter 2 at an energizing delay time t_{ed}=0.6 s with droplet spacings S/d_0 = 14 and 16, respectively. All images in the figures are enlarged at the same magnification. t indicates the elapsed time from ignition of Droplet I. As shown in Fig. 2, for both S/d_0 = 14 and 16, the flammable-mixture layer is formed eccentrically in the direction of Droplet I and elliptically judging from the shape of the initial flame and the positions of the SiC fibers suspending the droplets. The figure also shows that the flammable-mixture layer at S/d_0 = 14 is clearly larger than that at S/d_0 = 16. As the distance between the droplets is increased, the amount of heat transferred from the flame of Droplet I to Droplet A also decreases, and therefore the time required for forming a flammable-mixture layer becomes longer.

Next, a more detailed analysis on the flammable-mixture layer formation was performed by determining the major diameter of the ellipse of the initial flame as a representative diameter F of the flammable-mixture layer. Figure 3 shows graphs of the flammable-mixture layer diameter F vs. the normalized ignition delay time t_{id}/d_0^2 of Hot-wire igniter 2 for S/d_0 = 14 and 16. The horizontal axis shows the pre-heating time of Droplet A, which is the elapsed time from the ignition of Droplet I to the ignition of the flammable-mixture layer around Droplet A. The figure shows that in the case with a dimensionless pre-heating time t_{id}/ d_0^2=1.7 s/mm² or higher, F/ d_0 decreases by about 35% as S/d_0 changes from 14 to 16. On the other hand, no decrease in F/d_0 is observed in results where t_{id}/d_0^2 is less than 1.7 s/mm2. This experiment was conducted at a room temperature of around 283 K for all conditions of S/d_0 = 14 and experiments with a dimensionless pre-heating time t_{id}/d_0^2 = 1.7 s/mm² or higher for S/d_0 = 16. However, the experiments with a t_{id}/d_0^2 of less than 1.7 s/mm² and S/d_0 = 16 were conducted at a room temperature of around 303 K, so the formation of the flammable-mixture layer progressed more than under the lower-temperature conditions.

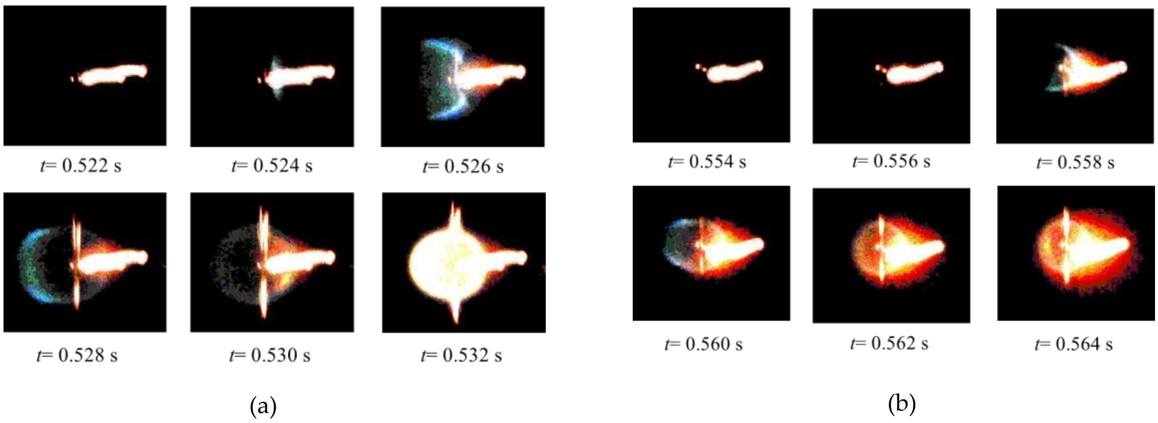

Fig. 2 Initial-flame formation through premixed-flame propagation in flammable-mixture layer for t_{ed} = 0.6 s of Hot-wire igniter 2 ((a) S/d_0 = 14, (b) S/d_0 = 16)

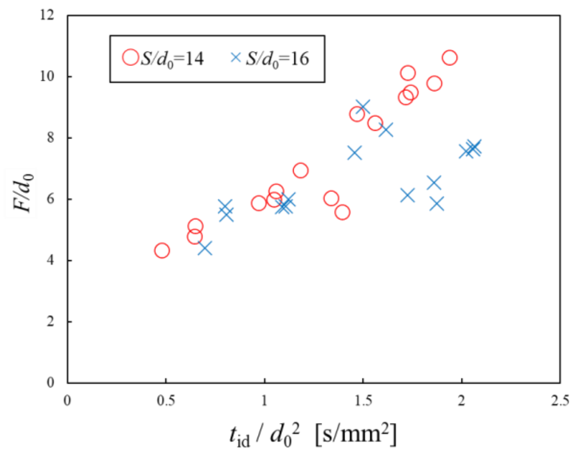

Fig. 3 Dependence of the flammable-mixture layer diameter F/d_0 on the pre-heating time t_{id}/d_0^2

4. Conclusions

This study investigated the effect of the distance between a burning droplet, Droplet I, and an unburned droplet, Droplet A, on a flammable-mixture layer formed around Droplet A existing outside the flammability limit of Droplet I in microgravity. The main findings are as follows.

1. The flammable-mixture-layer diameter is smaller for a larger droplet spacing under the same pre-heating time of Droplet A.

2. The formation of a flammable-mixture layer is facilitated by an increase in the ambient temperature.

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