ILASS–Europe 2019, 29th Conference on Liquid Atomization and Spray Systems, 2-4 September 2019, Paris, France

Study on large-scale ignition in the flame spread of randomly distributed droplet clouds near the group-combustion-excitation limit in microgravity

Kodai Matsumoto*[1], Yasuko Yoshida[1], Masato Mikami[1], Masao Kikuchi[2]

[1] Department of Mechanical Engineering, Yamaguchi University, Ube, Japan
[2] JEM Utilization Centre, Japan Aerospace Exploration Agency, Tsukuba, Japan
*Corresponding author: b059vd@yamaguchi-u.ac.jp

Abstract

In 2017, research on a droplet combustion experiment titled "Elucidation of Flame Spread and Group Combustion Excitation Mechanism of Randomly Distributed Droplet Clouds (Group Combustion)" was conducted aboard the International Space Station (ISS). A large-scale ignition phenomenon in which multiple droplets are ignited at the same time was observed, which has not been seen in past experiments. We hypothesised that unburned droplets existing outside the flame-spread limit were heated by a group flame and created a flammable mixture, or heated unburned droplets vaporized with cool flames. We carried out verification experiments using droplet-cloud elements, which are basic elements of randomly distributed droplet clouds. The flame surrounding the droplets heated a droplet existing outside the flame-spread limit and droplet vaporization was observed by a digital video camera with a back-light module. The droplet diameter was calculated, and the vaporization-rate constant was calculated. The experiments were conducted for different numbers and positions of burning droplets. The results showed that increasing the number of burning droplets increased the vaporization-rate constant of the heated droplets. The heated droplets were almost completely vaporized without the appearance of a hot-flame probably due to the cool-flame appearance. We conducted another experiment in which a droplet cluster was heated by a flame outside the flame-spread limit, and pre-vaporized, and then the formed flammable mixture was ignited from another flame. The flame appearing after the pre-vaporization was larger than the ordinary spreading flame. These results suggest that the pre-vaporization of the droplets gradually progresses due to the cool flame reaction occurring outside the flame-spread limit, leading to a large flame at the time of ignition. The large-scale ignition phenomenon in the randomly distributed droplet cloud probably occurred in the same way.

Key words

Flame spread, Droplet cloud, Group combustion, Microgravity

Introduction

Spray combustion is used in many combustors. Spray combustion is complicated because the atomization of liquid fuel, dispersion of droplets, vaporization of fuel, and chemical reaction progress simultaneously. In order to elucidate the fundamental aspects of spray combustion, many studies on droplet combustion in microgravity have been carried out, but there is still a large gap in understanding between droplet combustion studies and spray combustion studies. For example, although it is necessary to excite group combustion of the fuel spray in order to operate the spray combustor stably, the detailed mechanism of group combustion excitation has not been elucidated. Therefore, in 2017, droplet-cloud combustion experiments titled "Elucidation of Flame Spread and Group Combustion Excitation Mechanism of Randomly Distributed Droplet Clouds (Group Combustion)" [1] were conducted as the first combustion experiments in the Japanese Experimental Module "Kibo" aboard the International Space Station (ISS), in order to bridge the gap in understanding between droplet combustion studies and spray combustion studies. In Group Combustion Experiments, flame spread experiments over droplet-cloud elements with strong droplet interaction [2] and over randomly distributed droplet clouds [3-5] were respectively conducted to study the effects of droplet interaction on the flame spread and to study group-combustion-excitation characteristics in high-quality, long-duration microgravity aboard ISS. In the flame spread over a randomly distributed droplet cloud near the group-combustion-excitation limit, a large-scale ignition phenomenon in which multiple droplets are ignited at the same time was observed, which has not been seen in past experiments [4, 5]. Figure 1 shows an image of the flame-spread behavior near the group-combustion excitation [4]. Large-scale ignition can be seen in the lower left area in Fig. 1. In addition, under specific conditions of a randomly distributed droplet cloud, re-burning phenomenon by slow-flame propagation was also observed [5]. This phenomenon has also not been seen in past experiments.

This paper reports the large-scale ignition phenomenon observed in randomly distributed droplet clouds. We hypothesized that unburned droplets existing outside the flame-spread limit were pre-heated by a group flame and created a flammable mixture, and the large-scale ignition phenomenon occurred through ignition of the flammable mixture by a flame spreading through another path. We experimentally investigated the vaporization characteristics of an unburned droplet heated by a flame existing outside the flame-spread limit using droplet-cloud elements, which are basic elements of randomly distributed droplet clouds. Then, we verified the hypothesis by igniting the flammable mixture formed around multiple droplets heated by a flame existing outside the flame-spread limit to simulate large-scale ignition.

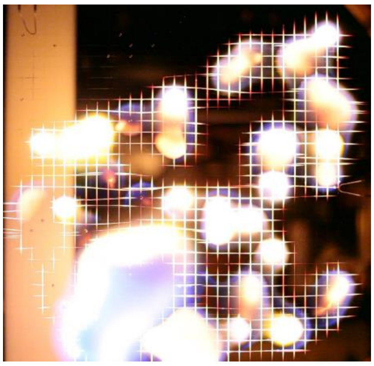


Figure 1. Lighten-composite image of flame-spread behavior with 1-s intervals of randomly distributed droplet clouds [4]. The large-scale ignition phenomenon in which multiple droplets are ignited at the same time can be seen in the lower left area.

Experimental Apparatus and Procedures

The experimental apparatus used in this research is explained in detail in Refs [6-8]. This section describes some important points and additional information.

Figure 2 shows a SiC-fiber lattice for droplet-cloud suspension. 14-μm SiC fibers (Nippon Carbon, Hi-Nicalon) were stretched in a 30×30 two-dimensional square lattice with 4-mm intervals. Droplets formed at the intersection of the SiC fibers. Four ignition units were installed in the droplet suspension device as shown in Fig. 2. In this study, we used an ignition unit for Exp. 1 mainly to start the flame spread by ignition of the droplet near the electrically heated resistance wire of the ignition unit.

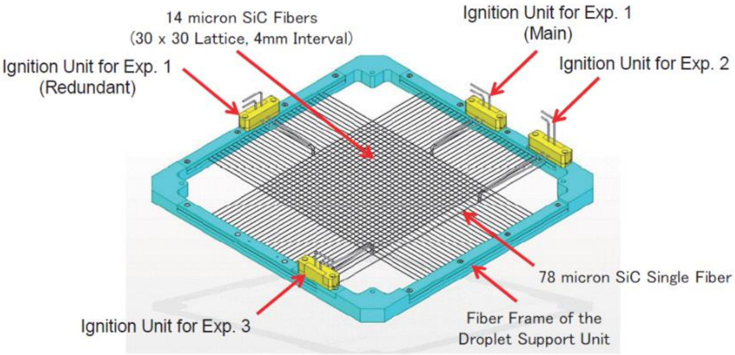


Figure 2. SiC-fiber lattice for droplet cloud suspension and ignition units [6].

Figure 3 shows the droplet-cloud generation device, which generates *n*-decane droplets at intersections of SiC fibers by supplying the fuel through a glass-tube needle [3, 4, 6]. A certain amount of fuel is pushed out from a stepping-motor-driven syringe and is delivered to the glass-tube through a Teflon tube. The top of the fuel-supply glass-tube needle is moved by a three-axis traverse system, and a droplet is generated at a designated lattice point. An LED backlight is installed in the moving stage.

A digital video camera (Canon, EOS 5D MarkII) took still images of droplet clouds and movies of burning behavior through the glass window of the chamber. The shooting speed of this camera was 30 fps. The spatial resolutions of the still image and the movie were 41.5 μm/pixel and 122 μm/pixel, respectively. We took images of droplet clouds with the LED backlight with a light-emitting area of 30×146 mm to measure the initial diameter of each droplet just before the ignition using still images and the droplet diameter during the flame spread using movie images based on the method described by Nomura et al. [9]. These devices were installed in the Group Combustion Experiment Module (GCEM).

The initial pressure was adjusted to be 0.1 MPa by supplying air from a cylinder. Since GCEM was installed inside the Chamber for Combustion Experiment (CCE) on the cold plate inside Work Volume (WV) of the Multi-Purpose Small Payload Rack (MSPR) in Kibo, the released heat from the apparatus and combustion inside the combustion chamber was transferred to the cold plate, and thus the air temperature inside the combustion chamber was maintained at 293 K in the initial condition.

In this study, we used a low-volatility fuel *n*-decane, and the droplet diameter change from the start of the first droplet generation to ignition was less than 1%. The local equivalence ratio in the gas phase at the droplet surface was 0.09 during the droplet generation process, which is much smaller than the low flammability limit. Therefore, the pre-vaporization did not affect the flame spread significantly [3, 4].

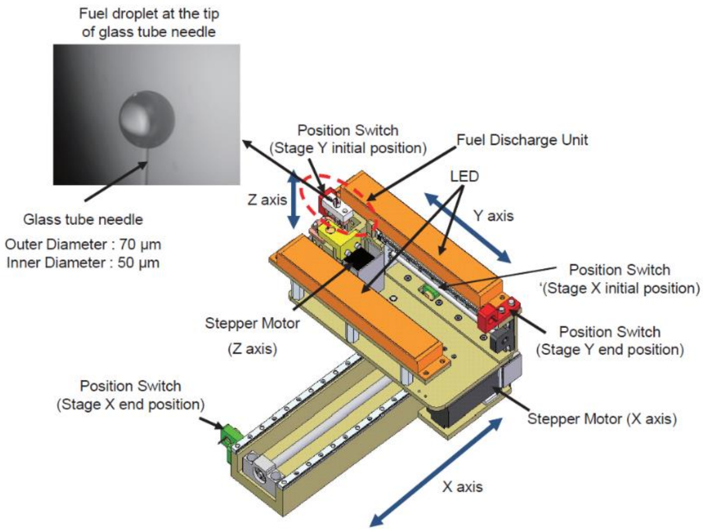
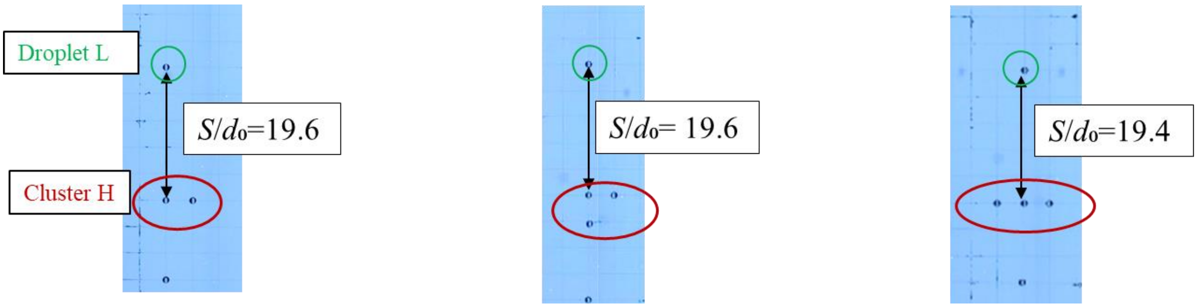


Figure 3. Droplet-cloud generation device [6].

Results and Discussion

Vaporization of Single Droplet Existing outside the Flame-spread limit

Figure 4 shows back-illuminated images of the droplet-cloud elements used to investigate the vaporization characteristics of an unburned droplet heated by a flame existing outside the flame-spread limit. We experimented on three different droplet-cloud elements with different droplet numbers or droplet arrangements in Cluster H. In each experiment, Droplet L was set outside the flame-spread limit of Cluster H. In this way, we altered the degree of heating by the flame of Cluster H. We experimented using a back-light module to measure the diameter of Droplet L after Cluster H ignition. We calculated the vaporization-rate constant of Droplet L using the result of temporal variation of the squared Droplet L diameter. In each condition, we show normalized droplet spacing S/d_0 between Droplet L and the droplet closest to Droplet L in Cluster H in Fig. 4, where d_0 is the initial droplet diameter.



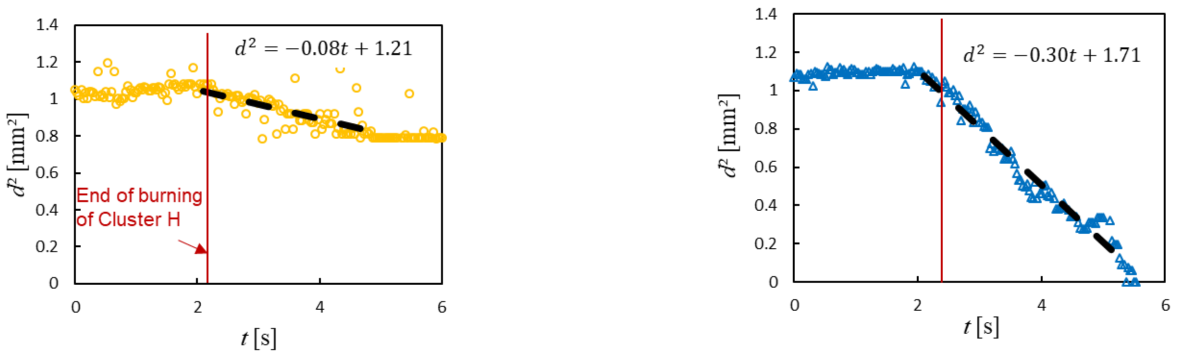
(a) Experiment A (b) Experiment B (c) Experiment C

Figure 4. Back-illuminated images of droplet-cloud elements with interactive burning droplets (Cluster H) to heat Droplet L existing outside the flame-spread limit.

Figure 5 shows temporal variations of the squared Droplet L diameter after the start of burning of Cluster H. We show approximate lines as black dashed lines while Droplet L gets a decrease in diameter, and the equation of each approximate line is shown in each figure. We calculated the absolute value of the slope of the approximate line as the vaporization-rate constant of Droplet L. For comparison, we show the temporal variation of the squared diameter of a burning droplet with a hot-flame in Fig. 5 (d).

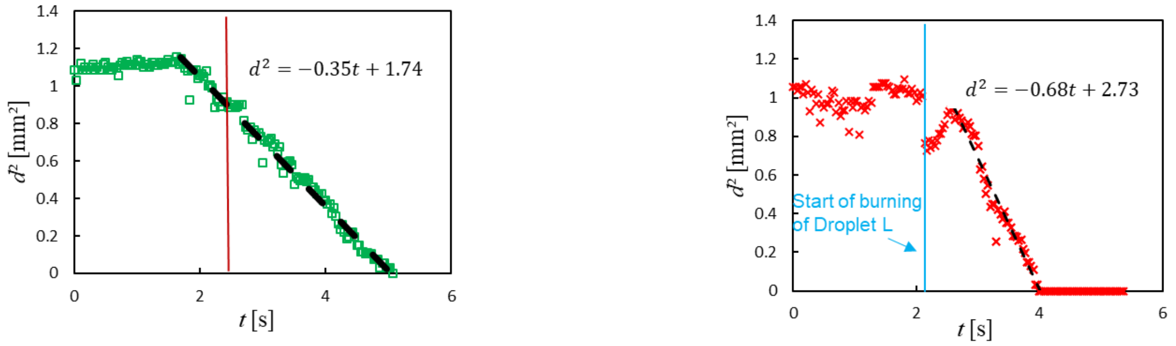
As shown in Fig. 5(a), a small amount of vaporization of Droplet L occurred in Experiment A. Droplet L did not vaporize completely. The vaporization of Droplet L continued for about 2 seconds. The vaporization-rate constant of Droplet L was K=0.08 mm^2/s.

As shown in Figs. 5(b) and 5(c), Droplet L vaporized completely in Experiments B and C. The vaporization-rate constants of Droplet L were K=0.30 mm^2/s in Experiment B and K=0.35 mm^2/s in Experiment C. These vaporization rates are greater than that in Experiment A but smaller than the burning-rate constant K=0.68 mm^2/s obtained in Experiment D shown in Fig. 5(d). In Experiments B and C, Cluster H continued burning for 2.2-2.3 seconds, and the vaporization of Droplet L continued for about 3.5 seconds. The vaporization lifetime of Droplet L was longer than the burning lifetime of Cluster H. Therefore, the vaporization of Droplet L in Experiments B and C was probably supported not only by the heat from the burning of Cluster H but also by a cool flame appearing around Droplet L. Nayagam et al. [10, 11] conducted combustion experiments of large single droplets aboard ISS and showed that the liquid hydrocarbon droplet of a few mm in initial diameter first vaporized with a hot-flame and then radiative extinction of the hot-flame occurred but the droplet vaporization continued with a cool-flame, while the vaporization-rate constant with the cool-flame is about 0.35 to 0.40 mm^2/s for *n*-decane droplets [11]. Although the experimental conditions of Ref. [11], such as the initial diameter of the droplet and the droplet pattern, were different from ours, the vaporization-rate constant of Droplet L in Experiments B and C was close to that in Ref. [11]. Therefore, we concluded that a cool-flame appeared around Droplet L in Experiments B and C.



(a) Experiment A

(b) Experiment B



(c) Experiment C

(d) Temporal variations of squared Droplet L diameter with hot flame.

Figure 5. Temporal variations of the squared diameter of Droplet L for different droplet-cloud elements. An approximation line during vaporization is also shown for each condition.

As for Droplet L in Experiment A, considering the vaporization-rate constant of Droplet L, the cool flame did not occur. In addition, Droplet L started to vaporize about 2 seconds after Cluster H ignition, and the duration of Droplet L vaporization was about 2.5 seconds. The vaporization of Droplet L was supported only by the heat from burning Cluster H.

Flame-Spread Behavior over Pre-heated Droplet Clusters

Figure 6 shows a back-illuminated image of the droplet arrangement used to simulate large-scale ignition. We used two types of droplet clusters: Cluster H with two droplets of 2 mm in initial diameter and Cluster L with five droplets of 1 mm in initial diameter. First, Cluster L is heated by the flame of burning Cluster H existing outside the flame-spread limit. Then, Cluster L is ignited by a flame spreading through a different path from the spreading flame to ignite Cluster H. As shown in Fig. 6, two of the same droplet arrangements were tested at the same time. Cluster L on the left side of Fig. 6 is arranged on the back-light module, so we can calculate the diameters of droplets in Cluster L. We observed the flame behavior around Cluster L using the right side of Fig. 6. In order to investigate the effect of pre-heating, we experimented without burning of Cluster H.

Figure 7 (a) shows the flame-spread behavior around Cluster L without pre-heating by burning of Cluster H. Droplet L5 ignited 0.70 seconds after Droplet I was ignited. Then, the flame spread to the other droplets of Cluster L, steadily. A group flame around Cluster L formed centring around Droplet L3.

Figure 7 (b) shows the flame-spread behavior around Cluster L with pre-heating by burning of Cluster H. Droplet I ignited 6.43 seconds after Droplet H1 of Cluster H was ignited. A large flame of multiple droplets started to propagate at the same time, forming a group flame around Cluster L. The group flame around Cluster L centred around Droplet L1, unlike in Fig. 7(a). As can be seen in Figs. 7(a) and 7(b), the group flame around Cluster L with pre-heating was bigger and shifted to the direction to Cluster H compared to that without pre-heating. These differences were caused by the effect of pre-heating by burning of Cluster H.

The large-scale ignition observed in the flame spread over a randomly distributed droplet cloud was reproduced well with the present experiment in the case with pre-heating by burning of Cluster H. This large-scale ignition was caused by a flammable mixture around Cluster L. That was formed by pre-heating by burning of Cluster H to Cluster L, and then the flammable mixture was ignited by the flame of Droplet I.

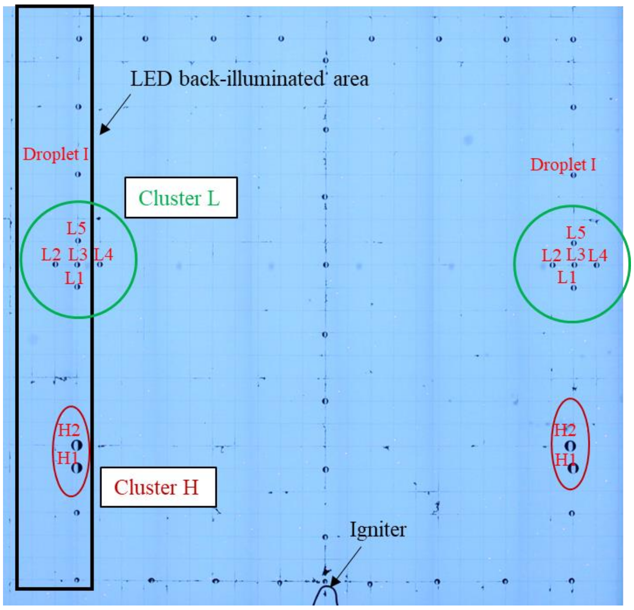
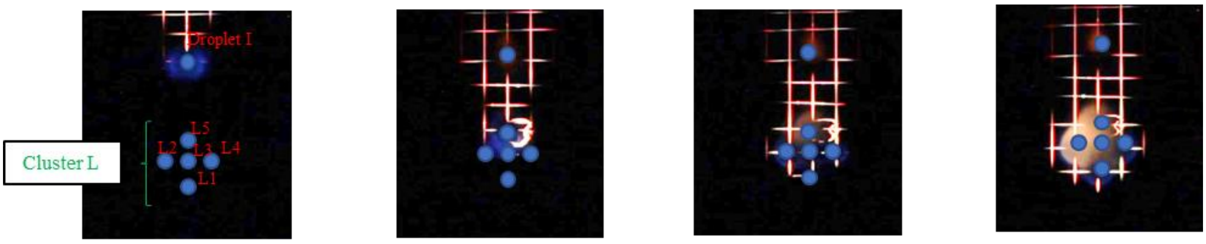


Figure 6. Back-illuminated image of droplet arrangement used to simulate the large-scale ignition.



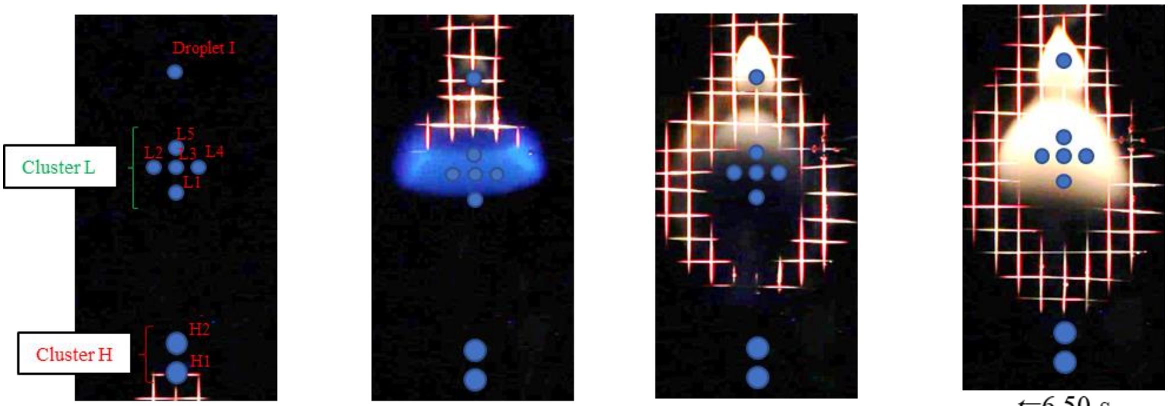
t'=0 s
Droplet I ignited

t'=0.70 s
Droplet L5 ignited

t'=0.73 s

t'=0.77s

(a) Flame-spread behavior without pre-heating by burning of Cluster H.



t=0 s
Droplet H1 ignited

t=6.43 s
Droplet I ignited

t=6.47s

t=6.50 s

(b) Flame-spread behavior with pre-heating by burning of Cluster H.

Figure 7. Flame-spread behavior of Cluster L without and with a large-scale ignition phenomenon

Figure 8 shows temporal variations of the squared droplet diameters in Cluster L with pre-heating by burning of Cluster H after the Cluster H was ignited. The red line in Fig. 8 shows the timing of the end of burning of Cluster H, and the black dashed line shows the timing of large-scale ignition.

Droplet L1 started to get a decrease in droplet diameter at about 4.5 second after Cluster H was ignited. The vaporization-rate constant of Droplet L1 until the large-scale ignition of Cluster L was 0.31 mm^2/s. This vaporization-rate constant is close to that with the cool-flame as discussed in the previous sub-section. Therefore, Droplet L1 vaporized with a cool flame.

Droplets L2 and L3 started to get a decrease in droplet diameter at about 5.5 seconds after Cluster H was ignited. The vaporization-rate constants of Droplets L2 and L3 until the large-scale ignition of Cluster L were respectively 0.20 mm^2/s and 0.21 mm^2/s. These vaporization-rate constants are smaller than that with the cool flame. Therefore, the vaporization of Droplets L2 and L3 was not supported by a cool flame but by burning of Cluster H alone. Droplet L5 did not get a decrease in droplet diameter until the large-scale ignition occurred.

A flammable mixture is formed by pre-heating an unburned droplet by a flame outside the flame-spread limit. When there are more droplets to be heated, a larger flammable mixture formed. Then, a larger-scale ignition phenomenon occurred by ignition of the flammable mixture. In a randomly distributed droplet cloud, the droplets showing large-scale ignition were pre-heated by a group flame around multiple droplets and by cool-flames partly to have a large-scale flammable mixture in the same way as in this experiment.

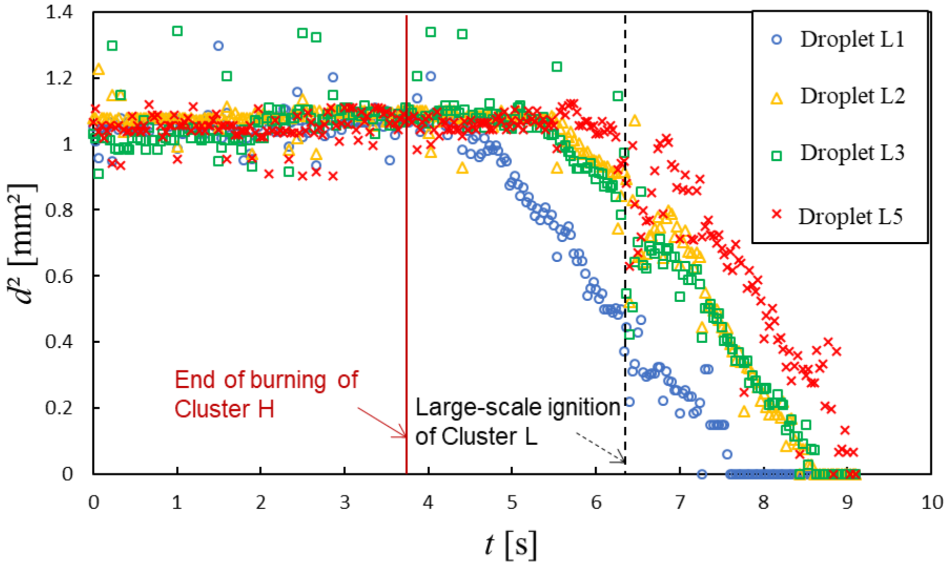


Figure 8. Temporal variations of the squared diameter of droplets in Cluster L in the case with the large-scale ignition phenomenon.

Conclusions

We investigated the large-scale ignition phenomenon observed in randomly distributed droplet clouds in microgravity aboard Kibo/ISS using droplet-cloud elements. We investigated the influence of heating by a flame existing outside the flame-spread limit on unburned droplets and the burning behavior of a pre-heated droplet cluster. The main conclusions are as follows:

(1) The vaporization of unburned droplets is supported by the heat transfer from the flame existing outside the flame-spread limit.
(2) The vaporization of unburned droplets is also supported by a cool flame even after the end of heat transfer if the heat transfer is greater than a certain value, so the flammable mixture forms around unburned droplets, rapidly.
(3) A large flammable mixture is formed by vaporization of multiple droplets with pre-heating by a flame outside the flame-spread limit. The cool-flame appears around some droplets and enhances vaporization. A large-scale ignition phenomenon, which is similar to that observed in randomly distributed droplet clouds, occurs by ignition of the large flammable mixture.

Acknowledgements

This research was conducted as part of the Kibo utilization experiments called “Group Combustion” by JAXA and was also subsidized by JSPS KAKENHI Grant-in-Aid for Scientific Research (B) (18H01625).

References

[1] Mikami, M., Kikuchi, M., Kan, Y., Seo, T., Nomura, H., Suganuma, Y., Moriue, O., Dietrich, D. L., Droplet cloud combustion experiment “Group Combustion” in KIBO on ISS, 2016, International Journal of Microgravity Science and Application, 33(2), 330208.

[2] Yoshida, Y., Iwai, K., Nagata, K., Seo, T., Mikami, M., Moriue, O., Sakashita, T., Kikuchi, M., Suzuki, T., Nokura, M., Flame-spread limit from interactive burning droplets in microgravity, 2019, Proceedings of the Combustion Institute, 37(3), pp. 3409-3416.

[3] Mikami, M., Nomura, H., Suganuma, Y., Kikuchi, M., Suzuki, T., Nokura, M., Generation of a Large-Scale n-Decane-Droplet Cloud Considering Droplet Pre-Vaporization in "Group Combustion" Experiments aboard Kibo/ISS, 2018, International Journal of Microgravity Science and Application, 35(2), 350202.
[4] Mikami, M., Yoshida, Y., Seo, T., Sakashita, T., Kikuchi, M., Suzuki, T., Nokura, M., Space-Based Microgravity Experiments on Flame Spread over Randomly Distributed n-Decane-Droplet Clouds: Overall Flame-Spread Characteristics, 2018, Microgravity Science and Technology, 30(4), pp. 535-542.
[5] Mikami, M., Yoshida, Y., Kikuchi, M., Dietrich, D. L., Anomalous Behaviour in Flame Spread over Randomly Distributed Droplet Clouds in Microgravity aboard Kibo in the ISS, July. 1.-5. 2019, 12th Asia-Pacific Conference on Combustion, Paper No. ASPACC2019-1504.
[6] Kikuchi, M., Kan, Y., Tazaki, A., Yamamoto, S., Nokura, M., Hanafusa, N., Hisashi, Y., Moriue, O, Nomura, H., Mikami, M., Current Status on Preparation of Fuel Droplet Clouds Combustion Experiment “Group Combustion” Onboard the KIBO, 2014, Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan, 12 (ists29), pp. Th_25-Th_30,
[7] Mikami, M., Oyagi, H., Kojima, N., Kikuchi, M., Wakashima, Y., Yoda, S. Microgravity experiments on flame spread along fuel-droplet arrays using a new droplet-generation technique, 2005, Combustion and Flame, 141(3), 241-252.
[8] Mikami, M., Watari, H., Hirose, T., Seo, T., Saputro, H., Moriue, O., Kikuchi, M., Flame spread of droplet-cloud elements with two-droplet interaction in microgravity, 2017, Journal of Thermal Science and Technology, 12, pp. 1-10.
[9] Nomura, H., Takahashi, H., Suganuma, Y., Kikuchi, M. Droplet ignition behaviour in the vicinity of the leading edge of a flame spreading along a fuel droplet array in fuel-vapor/air mixture, 2013, Proceedings of the Combustion Institute, 34(1), pp.1593-1600.
[10] Nayagam, V., Dietrich, D. L., Ferkul, P. V., Hicks, M. C., Williams, F. A., Can cool flames support quasi-steady alkane droplet burning?, 2012, Combustion and Flame 159 (12), pp. 3583-3588.
[11] Nayagam, V., Dietrich, D. L., Hicks, M. C., Williams, F. A., Cool-flame extinction during n-alkane droplet combustion in microgravity, 2015, Combustion and Flame, 162(5), pp. 2140-2147.