Int. J. Microgravity Sci. Appl., **33** (2) (2016) 330208
DOI: 10.15011/jasma.33. 330208

IIIII ISPS-6 Proceedings IIIII
(Review)

Droplet Cloud Combustion Experiment "Group Combustion" in KIBO on ISS

Masato MIKAMI[1], Masao KIKUCHI[2], Yuji KAN[2], Takehiko SEO[1], Hiroshi NOMURA[3], Yusuke SUGANUMA[3], Osamu MORIUE[4] and Daniel L. DIETRICH[5]

Abstract

Flame spread in fuel spray near the flame base and subsequent excitation of group combustion of the whole spray are necessary for stable combustion of continuous burning of liquid fuel such as in aero engines or gas turbines. In order to elucidate the flame spread mechanism, flame spread experiments of a fuel-droplet array in microgravity have been undertaken. Based on the past short-duration microgravity experiments and a percolation model to describe group combustion excitation of randomly distributed droplet clouds, the droplet cloud combustion experiment named "Group Combustion" is planned as the first combustion experiment in the Japanese Experiment Module "KIBO" on the International Space Station. The objective of this experiment is to verify the flame spread hypotheses regarding the effects of droplet interaction, droplet motion, and radiative heat loss from the flame. The Group Combustion Experiment Module (GCEM) has been developed as experiment-dedicated apparatus. This paper will provide an overview of the experiment.

Keyword(s): Microgravity combustion experiment, Droplet cloud, Flame spread, Group combustion, KIBO/ISS.
Received 30 September 2015; Accepted 28 November 2015; Published 30 April 2016

1. Introduction

Spray combustion is widely utilized in diesel engines, jet engines, gas turbines, boilers, etc. However, the mechanism of spray combustion has not yet been completely clarified because it is a very complicated phenomenon in which many processes, such as liquid atomization, droplet dispersion in the gas phase, vaporization and chemical reaction, simultaneously proceed with interaction.

Figure 1 shows a typical photograph of spray combustion. A number of droplets generated through the injection burns with a group flame surrounding them. This type of combustion is called group combustion. Stable combustion in practical combustors requires group combustion. What controls group combustion excitation? What is the role of droplets in group combustion excitation? In order to answer these questions, we have planned and prepared a droplet cloud combustion experiment entitled "Elucidation of Flame Spread and Group Combustion Excitation Mechanism of Randomly Distributed Droplet Clouds (Group Combustion)" using the Japanese Experimental Module "KIBO" on the International Space Station, ISS. This paper describes the background and preparatory state of this space experiment.

Fig. 1 Combustion of fuel spray.

2. Flame Spread between Droplets and Group Combustion Excitation

2.1 Importance of a Microgravity Environment in a Droplet Combustion Experiment

Microgravity experiments on droplet combustion were started over half a century ago by Kumagai and Isoda[1)] as a fundamental research into spray combustion, considering fuel droplets, an element of fuel spray. Since the droplet combustion process contains heat and mass transfer both in the gas phase and liquid phase and phase equilibrium, it is the most basic configuration of combustion of a heterogeneous fuel system. This experiment was also the first scientific experiment in microgravity on earth in the world. Since Kumagai and Isoda[1)],

1 Graduate School of Sciences and Technology for Innovation, 2-16-1 Tokiwadai, Ube, Yamaguchi755-8611, Japan.
2 JEM Utilization Center, Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba, Ibaraki305-8605, Japan.
3 College of Industrial Technology, Nihon University, 1-2-1 Izumi-cho, Narashino, Chiba275-8575, Japan.
4 Faculty of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka819-0395, Japan.
5 Glenn Research Center, National Aeronautics and Space Administration, 21000 Brookpark Rd, Cleveland, OH 44135, USA.
(E-mail: mmikami@yamaguchi-u.ac.jp)

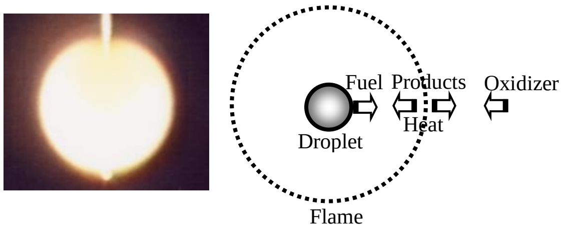


Fig. 2 Spherical combustion of a single fuel droplet in microgravity.

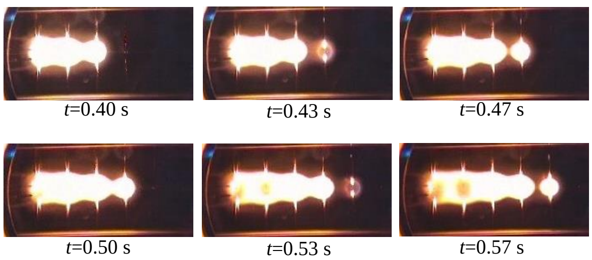


Fig. 3 Flame-spread behavior of n-decane droplet array at T_a=600 K in microgravity[7].

a variety of combustion experiments including droplet combustion have been conducted in microgravity[2].

Figure 2 shows a direct photograph and a schematic of spherical combustion of a fuel droplet in microgravity. Processes around a droplet occur in a spherically symmetric and one-dimensional manner in microgravity, while in normal gravity, the flame shape is elongated by buoyancy-induced flow, i.e., natural convection, since there is a large density difference between the flame and the ambient air.

Since the droplet size in practical spray combustion is very small, in the order of 10 microns, the gravitational effect on processes around each droplet is negligibly small even in normal gravity. On the other hand, when a large droplet of about 1 mm is burned to observe behavior with high resolution in normal gravity, the buoyancy effect is significant and the behavior is therefore different from that with fine droplets. In order to investigate droplet combustion phenomena in detail with large droplets, a microgravity condition is required to avoid the buoyancy effect.

As mentioned above, the microgravity environment has the positive effects of simplification of phenomena and improvement of resolution in time and space and is therefore an idealized condition to understand extreme characteristics of combustion phenomena. Since the pioneering work by Kumagai and Isoda[1], many researches on liquid fuel combustion have been conducted in microgravity[3, 4]. Microgravity experiments on single-droplet and multiple-droplet combustion will contribute to verification and improvement of spray combustion simulation codes by offering fundamental data. Sub-models, such as radiation models, chemical reaction models, etc., are verified using combustion experiment data obtained under such an idealized condition.

2.2 Flame Spread between Droplets

Unlike the single-droplet combustion shown in **Fig. 2**, a number of droplets are burned with a group flame surrounding them in spray combustion as shown in **Fig. 1**. Burning behavior is affected by the interaction of droplet-scale phenomena. Not only single-droplet combustion but multiple-droplet combustion, such as combustion of two droplets, droplet array and droplet cloud, have been actively researched, making efforts to link knowledge from droplet combustion to elucidation of spray combustion mechanisms. Since flame spreading between droplets appears near the base of group flames formed in continuously supplied sprays, fundamental researches on flame spread between droplets have actively been conducted in microgravity[5-12]. This section describes the flame spread between droplets, which is one of the important concepts in "Group Combustion" experiments, which are the droplet cloud experiments to be performed in "KIBO" on ISS.

Mikami et al.[6, 7] developed a technique to simultaneously generate multipe droplets at intersections of 14 μm SiC fibers by supplying liquid fuel through fine glass needles and conducted flame-spread experiments on a droplet array at high temperatures of up to 750 K in microgravity. Typical flame-spread behavior at high temperature is shown in **Fig. 3**. Mikami et al. [7] showed that normalized flame-spread rate $V_f d_0$ attains maximum at specific dimensionless droplet spacing S/d_0 at relatively low temperatures (**Fig. 4**). They also explain that the maximum is caused by the rate-control process change from the droplet heating for vaporization activation to the thermal conduction from the high-temperature region around a burning

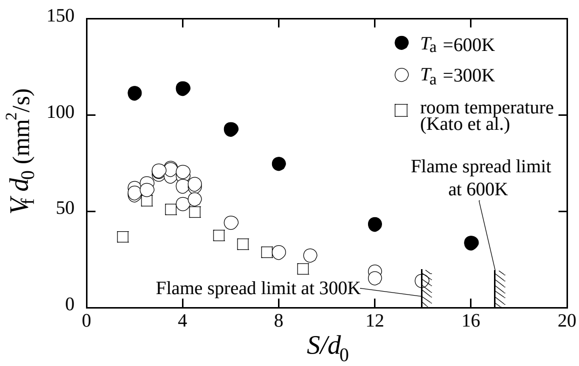


Fig. 4 Dependence of flame-spread rate on droplet spacing for n-decane droplet array at different ambient temperatures in microgravity[7].

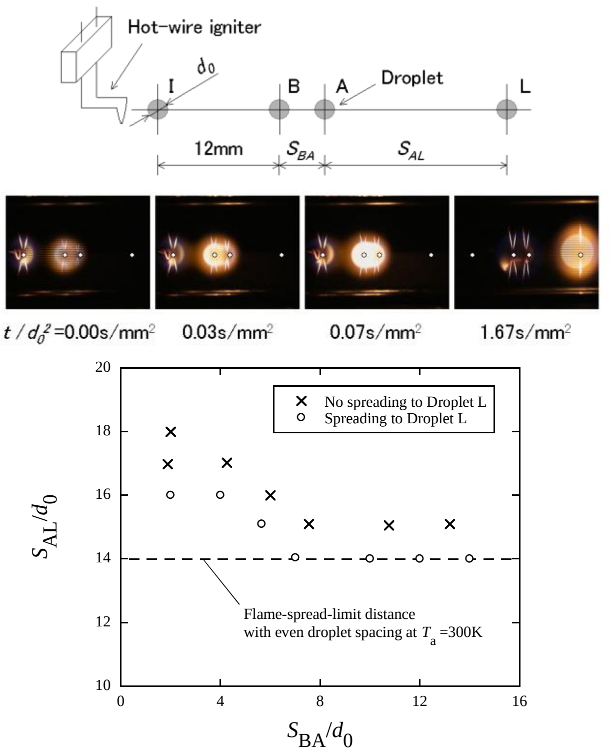


Fig. 5 Droplet-array model with uneven droplet spacing (upper), typical burning behavior (middle) and dependence of flame-spread-limit distance on local droplet interaction (lower) [8].

droplet and that the development of a flammable mixture layer around the unburned droplet increases the flame-spread rate. Another important characteristic is the flame-spread limit $(S/d_0)_{limit}$, over which the flame cannot spread to the next unburned droplet. It is about $(S/d_0)_{limit}$=14 for an n-decane droplet array with even droplet spacing in microgravity (**Fig. 4**) and greater at a higher temperature[7].

Oyagi et al.[8] extended these experiments to flame-spread experiments of a droplet array with uneven droplet spacing in microgravity. The results show that local droplet interaction increases the flame-spread limit distance to the next droplet (**Fig.5**).

The findings described above motivated the droplet cloud combustion experiment "Group Combustion" to be performed in "KIBO" on ISS, which was accepted as a space experiment candidate in 2008.

Recently, Mikami et al.[12] conducted flame-spread experiments using droplet-cloud elements in microgravity, as shown in **Fig. 6**, which are basic elements of a randomly distributed droplet cloud at the critical condition based on the percolation model to be explained in Section 2.3. They showed that the flame-spread rate and limit are affected by the flame-spread direction from the two interactive burning droplets as shown in **Fig. 6**.

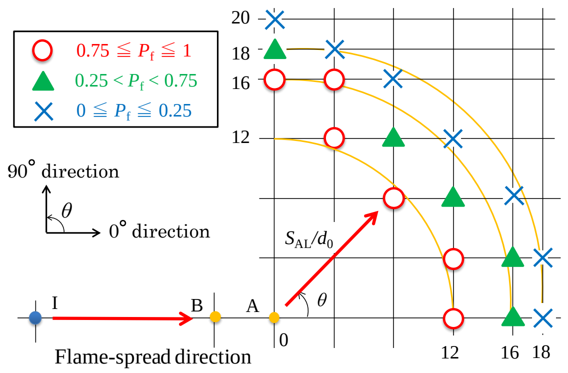
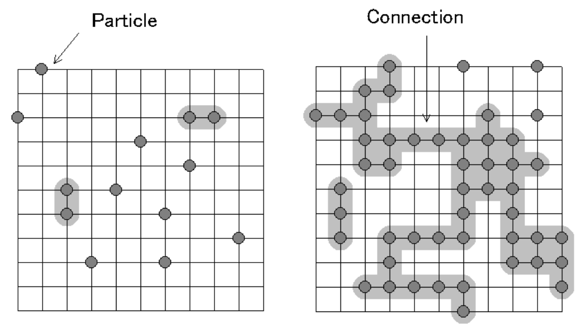


Fig. 6 Flame-spread-limit distribution around two-droplet burning with S_{BA}/d_0=4[12].



(a) Small number of particles (b) Large number of particles

Fig. 7 Particle connections and occurrence of a large-scale cluster[8].

2.3 Percolation Model to Describe Group Combustion Excitation

This section explains the percolation model that describes group combustion excitation, which is another important concept in the "Group Combustion" experiments to be performed in "KIBO" on ISS.

The flame cannot spread to the next unburned droplet in a droplet array if the droplet spacing is over the flame-spread limit. Is there anything like the flame-spread limit in droplet clouds? If the droplet cloud becomes too dilute, the flame will not reach all regions of the droplet cloud.

We define group combustion excitation as the state in which the effect of local droplet combustion, i.e., the burning region, spreads over the whole droplet cloud. By applying the percolation theory[13], which explains that the local particle connection rule determines the characteristics of randomly distributed particle clouds, some researches have been conducted to elucidate the relationship between the local flame spread between droplets and flame spreading over the droplet cloud, leading group combustion excitation[8, 14-16]. As shown in **Fig. 7**, if the occupation fraction of number of particles in the total number of lattice points is relatively small, the particle connection generated by particles existing next to each other is short. On the other hand, as the occupation fraction is increased, the particle connection lengthens and finally reaches the scale of the particle cloud size, resulting in a large-scale cluster. If the percolation theory is applied to spray combustion, the droplet, flame spreading and group combustion are respectively treated as the particle, connection, and large-scale cluster. The percolation model explains that the local flame-spread rule determines group combustion excitation characteristics and possibly provides knowledge on the limit of the equivalence ratio over which the group combustion of a fuel spray can be excited, which is important practically.

Figure 8 shows the percolation model considering the flame-spread-limit distance[8,15]. The flame can spread to droplets within the flame-spread-limit distance but cannot spread to the droplets outside it. **Figure 9** shows the dependence of group combustion occurrence probability on the mean droplet spacing of a randomly distributed droplet cloud. This graph suggests that there is the critical condition where a transition occurs between partial combustion and group combustion. This transition is possibly identical to the transition between incomplete combustion and stabilized combustion in practical combustors.

The local flame-spread-limit distance is important in the percolation model. However, it is possibly affected by local droplet interaction. Around the critical condition which is the group combustion excitation limit, the mean droplet spacing is relatively large, and therefore, the mean effect of droplet interaction is relatively small in the droplet cloud. However, there exist large-droplet-spacing regions and small-droplet-spacing regions, in the latter of which the droplet interactive effect would be significant. In order to elucidate the local interactive effect on the flame-spread limit, Oyagi et al.[8] performed a flame-spread experiment over droplet arrays with

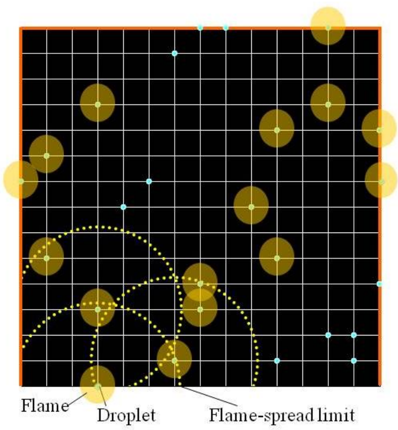


Fig. 8 Percolation model for group-combustion excitation through flame spread between droplets considering the flame-spread limit.

uneven droplet spacing in microgravity. As shown in **Fig. 5**, the droplet interaction between Droplets B and A increases the flame-spread limit from Droplets A to L. Oyagi et al.[8] employed this result in the percolation model for the flame spread over randomly arranged one-dimensional droplet arrays and showed that the critical condition is affected by local two-droplet interaction. Recently, Mikami et al.[12] conducted microgravity experiments on the flame spread of droplet-cloud elements and obtained the flame-spread-limit distribution around two interactive burning droplets as shown in **Fig. 6**. Saputro et al.[16] numerically showed that this distribution affects the critical condition in the percolation model.

3. Droplet Cloud Combustion Experiment in KIBO/ISS

An experimental theme on droplet cloud combustion "Elucidation of Flame Spread and Group Combustion Excitation Mechanism of Randomly Distributed Droplet Clouds (Group Combustion)" using the Japanese Experimental Module "KIBO" on ISS was accepted in 2008 and has been prepared for a space experiment to be performed in the near future.

As mentioned in the previous chapter, the percolation theory predicts that a transition occurs at the critical droplet-number density or mean droplet spacing between partial combustion and group combustion of fuel sprays in flame spreading over randomly distributed droplet clouds (**Fig. 9**). This transition is possibly identical to the transition between incomplete combustion and stabilized combustion in practical combustors. Application of the percolation theory to flame spread over droplet clouds requires information on the local flame-spread rule.

"Group Combustion" experiments are roughly classified into three types of experiments which respectively verify the following three hypotheses on the local flame-spread rule:

1: The flame-spread-limit distance is affected by multiple-droplet combustion and depends on the flame-spread direction.
2: The flame-spread-limit distance between movable droplets is affected by asymmetric vaporization and combustion near the leading edge of the spreading flame.
3: The flame-spread-limit distance and flame-spread rate are affected by radiative heat loss.

In Experiment 1, the flame-spread-limit distribution around two interactive droplets is investigated using droplet-cloud elements similar to that in **Fig. 6**. The effect of three-droplet interaction is also studied. In addition to these experiments on the local flame-spread rule, the flame spread over randomly distributed droplet clouds around the critical condition predicted by the percolation model (**Fig. 9**) are also conducted with up to

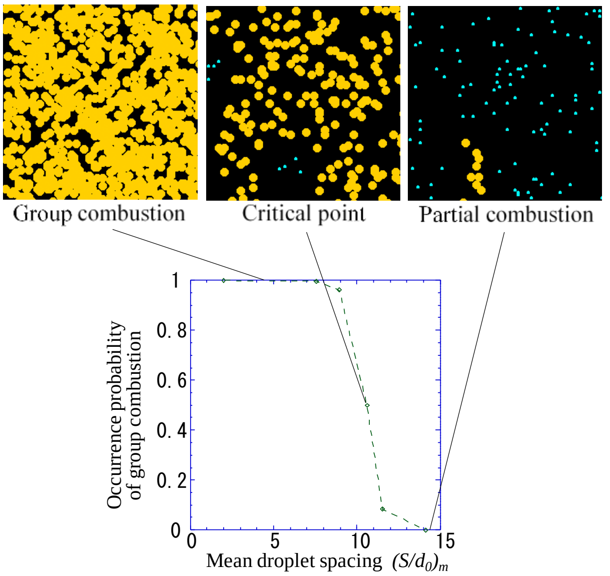


Fig. 9 Dependence of occurrence probability of group combustion and flame patterns on mean droplet spacing of randomly distributed droplet cloud for two-dimensional droplet arrangement.

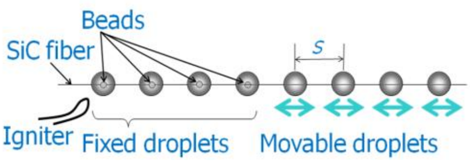


Fig. 10 Droplet array model with movable droplets on fiber.

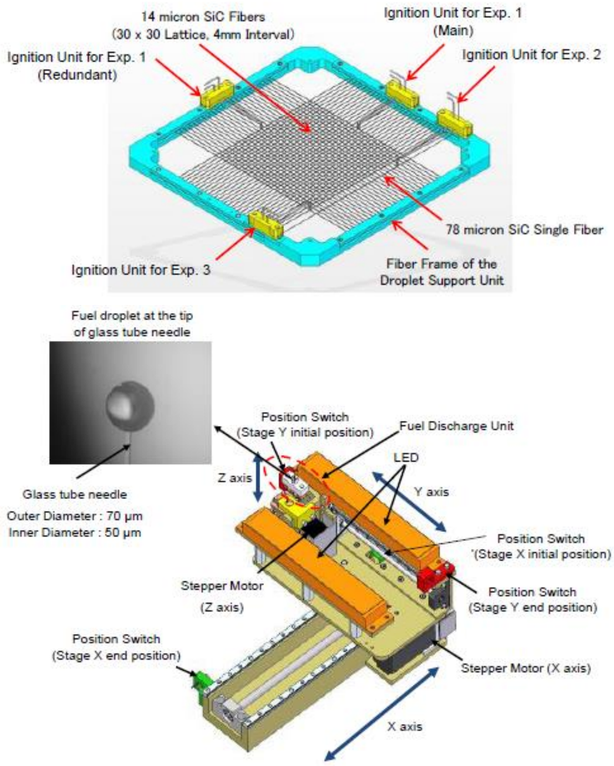


Fig. 11 SiC fiber lattice for droplet cloud suspension (upper), glass needle for droplet generation and three-dimensional traverse system (lower)[17].

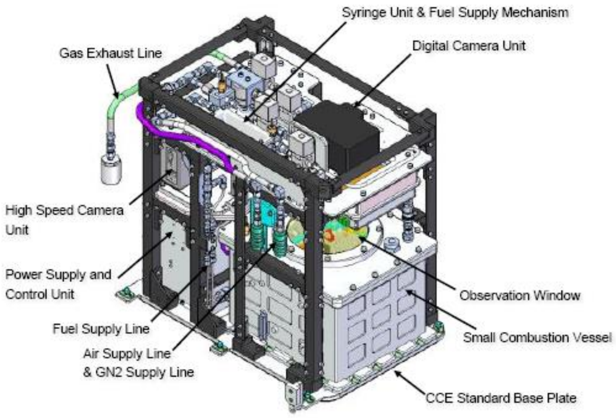


Fig. 12 Group Combustion Experiment Module (GCEM)[17].

152 droplets to check the local flame-spread rule and macroscopic flame-spread characteristics. Droplets of 1 mm in initial diameter are arranged at intersections of 30x30 14 μm SiC fiber lattice. A droplet on one side of the lattice is ignited to start flame spreading.

In Experiment 2, the effect of free droplets on the flame-spread limit is studied. In actual sprays, the droplets are not fixed in space and can therefore be moved by asymmetric vaporization during flame spreading[18]. On the other hand, the droplet motion may affect the flame spread. In order to investigate these effects, four fixed droplets and multiple movable droplets are arranged on a 78 μm SiC fiber as shown in **Fig. 10**, and the ignition behavior of each movable droplet and droplet motion during flame spreading are observed in detail.

In Experiment 3, the flame spread from a flame surrounding a droplet cluster to another droplet cluster is examined from the viewpoint of radiative heat loss, which is proportional to the third power of flame diameter[19]. Since the flame around the droplet cluster is greater than the flame around a single droplet, the radiative heat loss is significant and will affect the flame-spread limit. The initial droplet diameter is varied from 0.7-2.0 mm, and the oxygen concentration of the ambient gas is varied from 17–21 %, to vary the flame diameter. The droplet cluster consists of two or five droplets. The droplets are arranged at intersections of 14 μm SiC fibers like in Experiment 1.

In Experiments 1 and 3, the fuel-supply glass needle traversed three dimensionally generates droplet-cloud elements, randomly distributed droplet clouds and droplet clusters on intersections of 30x30 14 μm SiC fiber lattice with 4 mm fiber intervals. The upper part of **Fig. 11** shows the SiC fiber lattice and the lower part shows the fuel-supply glass needle and three-dimensional traverse system[17]. A 78 μm SiC fiber is placed in a different position from the fiber lattice, for Experiment 2 with movable droplets. n-Decane is used as a fuel. The fuel is stored in the syringe unit, pushed by a stepping motor and supplied through a Teflon tube to the glass needle with about 70 μm at the tip to form the droplet on the SiC fiber. Droplets are formed repeatedly one by one. Ignition is conducted by electric heating of a resistance wire placed near the droplet for ignition. A fan-shaped jet of nitrogen blows soot attached on the fiber and the unburned droplets. These apparatuses are installed inside the combustion vessel with about 13 L.

Although the fuel n-decane is a low-volatility fuel, the droplet diameter change is not negligible due to pre-vaporization during droplet cloud generation. We control the generated droplet size considering the vaporization rate so that the initial droplet diameters at ignition are within the required range. Since the gas-phase equivalence ratio at the n-decane droplet surface is about 0.1 at room temperature, which is below the lean flammability limit, the pre-vaporization effect on flame spread will be negligible.

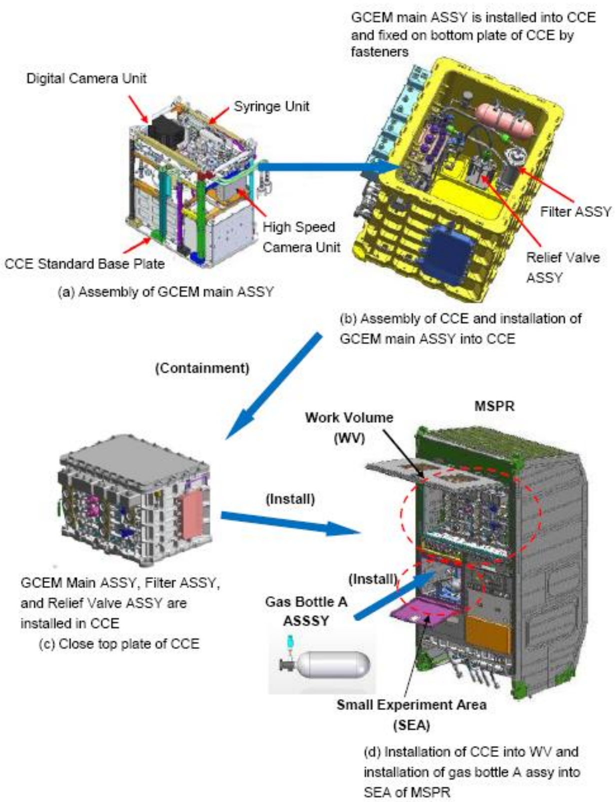


Fig. 13 Installation of GCEM in Multi-purpose Small Payload Rack (MSPR) in KIBO/ISS [17].

Figure 12 shows the Group Combustion Experiment Module (GCEM). As shown in **Fig. 13**, GCEM is installed in the Chamber for Combustion Experiment (CCE) to satisfy the double-seal condition. CCE is installed in the work volume (WV) of the Multi-purpose Small Payload Rack (MSPR) in "KIBO" on ISS. A digital video camera in Experiments 1 and 3 and a high-speed video camera in Experiment 2 capture the droplet generation process and the flame-spread behavior through the glass window of the combustion vessel. Still images with higher resolution are also recorded to check the initial droplet arrangement and to measure the initial size of each droplet before ignition. Experiments 2 and 3 employ a blinking back-illumination so as to obtain the direct image and the back-illuminated image alternately. The temperature field is measured by the TFP (thin-filament pyrometry) method based on visible radiation from SiC fibers in the high-temperature region around the flame [12]. The response time to the gas temperature variation is about 1 ms and sufficiently fast[12]. The effect of SiC fiber on the droplet shape, vaporization and combustion has been reported by Mikami et al.[6].

The nitrogen gas required for the removal of soot and unburned droplets on fibers is supplied from a GN_2 line of ISS to GCEM through CCE. The air required for all the experiments is supplied from a gas bottle installed in the Small Experiment Area (SEA) of MSPR to GCEM through CCE. The burned gas is evacuated from the combustion vessel through a filter. When the oxygen concentration of the gas inside the vessel is changed in Experiment 3, the vessel is evacuated first and then is filled with air from the gas bottle in SEA and nitrogen from the GN_2 line to regulate the oxygen concentration based on the partial pressure of each gas.

GCEM was safely delivered to ISS by the H-II Transfer Vehicle "KOUNOTORI5" (HTV5) launched by the H-IIB rocket on August 19, 2015. Although some required equipment, such as cameras, was lost in the accident of SpaceX-7 in June, 2015, we are preparing the equipment for another launch in the near future.

4. Concluding Remarks

The droplet cloud combustion experiment in space "Group Combustion" is the first combustion experiment in "KIBO" on ISS (**Fig. 14**). The experiment will make it possible to bridge the gap theoretically between droplet combustion and spray combustion, having a significant impact on the academic field of combustion science. Percolation theory, which can be widely applied to physical phenomena, has been applied to spray combustion and will be improved through such research. This will also have a strong impact on industries; the research will give a clear guideline for designing a spray combustor with

Fig. 14 Mission patch of "Group Combustion" experiment in KIBO/ISS (source: JAXA).

stable combustion. The knowledge will contribute to improvement of understanding combustion of general fuel-dispersed systems, such as proposing a fire safety standard to prevent dust explosion.

References

1) S. Kumagai and H. Isoda: Proc. Combust. Inst. **726** (1957) 6.
2) M. Kono, K. Ito, T. Niioka, T. Kadota and J. Sato: Proc. Combust. Inst, **1189** (1996)26.
3) M. Mikami: JASMA 25, **58** (2008)25.
4) M. Mikami: J. Combust. Soc. Japan, **196** (2008)50.
5) S. Kato, H. Kobayashi, H. Mizuno and T. Niioka: T., JSME Int. J. B,: **322** (1998)41.
6) M. Mikami, H. Oyagi, N. Kojima, Y. Wakashima, M. Kikuchi, and S. Yoda: Combust. Flame, **241** (2005) 141.
7) M. Mikami, H. Oyagi, N. Kojima, Y. Wakashima, M. Kikuchi, and S. Yoda: Combust. Flame, **391** (2006)146.
8) H. Oyagi, H. Shigeno, M. Mikami and N. Kojima: Combust. Flame, **763** (2009)156.
9) M. Kikuchi, S. Yamamoto, S. Yoda, M. Mikami, H. Nomura, O. Moriue, A. Umemura, Y. Hisashi, N. Sugano, K. Moesl, T. Sattelmayer, C. Eigenbrod and O. Minster: ESA SP, **473** (2011)700.
10) K.G. Moesl, T. Sattelmayer, C. Eigenbrod, M. Kikuchi, S. Yamamoto, S. Yoda, M. Mikami, H. Nomura, O. Moriue, A. Umemura, Y. Hisashi and N. Sugano: ESA SP, **487** (2011)700.
11) Mikami, N. Sano, H. Saputro: H. Watar:, T. Seo, Int. J. Microgravity Sci. Appl., **172** (2014)31.
12) M. Mikami, T. Hirose, H. Watari, T. Seo, O. Moriue and M. Kikuchi, ILASS-Europe 2013, Chania, Crete, (2013).
13) D. Stauffer and A. Aharony, Introduction to Percolation Theory (Revised 2nd Ed.), CRC Press, (1994).
14) A. Umemura and S. Takamori: Combust. Flame, **336** (2005)141.
15) H. Shigeno, H. Oyagi, M. Mikami and N. Kojima, ISTS 2006, 2006-h-24, Kanazawa, (2006).
16) H. Saputro, T. Seo and M. Mikami, Proc.17th Annual Conference of ILASS-Asia, ILASS-Asia2014-058, (2014).
17) M. Kikuchi, Y. Kan, A. Tazaki, S. Yamamoto, M. Nokura, N. Hanafusa, Y. Hisashi, O. Moriue, H. Nomura and M. Mikami, ISTS 2013, 2013-h-22, Nagoya, (2013).
18) H. Nomura, M. Takahashi, Y. Ujiie and H. Hara, Proc. Combust. Inst., **1991** (2005)30.
19) P.M. Struk, D.L. Dietrich, M. Ikegami, G. Xu, Proc. Combust. Inst., **609** (2002)29.