Int. J. Microgravity Sci. Appl., **36** (3) (2019) 360302
DOI: 10.15011//jasma.36.360302

IIII Review IIII

Hardware Development, Preparation, and Execution of the "Group Combustion" Experiment – as the First Combustion Experiment in KIBO –

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Abstract

The Group Combustion experiment was performed on the orbit from September 2016 to July 2017, as the first combustion experiment in Kibo. For the on-orbit experiment, the Group Combustion Experiment Module (GCEM) was developed by JAXA. Main components of the GCEM was launched by the HTV-5 in August 2015. Through the preparation of the experiment, there were several technical challenges as well as unexpected difficulties including the loss of the camera units of the experimental apparatus by the launch failure of SpX-7 mission. In addition, the on-orbit experiment faced multiple technical issues during the operation. The user integration (UI) team and the investigators conquered such issues one by one, with close cooperation and ingenuity. As a result, acquisition of experimental data that are beyond expectation was achieved. In this review, various efforts for development of the experimental apparatus as well as the efforts on preparation and execution of the on-orbit experiment are introduced.

Keyword(s): Group combustion, Droplets combustion, Flame spread, GCEM, Microgravity

Received 14 June 2019, accepted 8 July 2019, published 31 July 2019.

1. Introduction

A fuel-droplets combustion experiment, named "Group Combustion", began in the Kibo onboard the International Space Station (ISS) in September 2016. The exact title of the experiment is "Elucidation of Flame Spread and Group Combustion Excitation Mechanism of Randomly Distributed Droplet Clouds". The Principal Investigator (PI) of the experiment is Prof. Masato Mikami of Yamaguchi University, Japan. The experiment was selected by Japan Aerospace Exploration Agency (JAXA) as a candidate of the Kibo utilization experiments in February 2008. It took more than 8 years since its selection until the start of the on-orbit experiments. To reach the start point of the experiments in Kibo, a team consisting of PI, Co-Investigators (CIs), engineers in the hardware provider, contractors who support preparation on the on-orbit experimental plan and the operation plan, contractors who support preliminary tests on the ground, and user integrators in JAXA, has worked together in close cooperation. Through the preparation of the experiment in years, the team faced various difficulties. Not only technical challenges but also unexpected situations including the loss of the camera units of the experimental apparatus by the launch failure of SpX-7 mission in June 2015, described more detail in later, are part of such difficulties. Beyond some technical issues of the experimental apparatus, the Group Combustion experiment was successfully performed as the first combustion experiment in Kibo, finally.

In this paper, various efforts for development of the experimental apparatus as well as the efforts on preparation and execution of the on-orbit experiment are introduced.

2. Overview of the Experiment

The objective of the "Group Combustion" experiment is to investigate the hypothesis on the effects of droplet interaction, droplet motion, and radiative heat loss from the flame on the local flame-spread rule among fuel droplets. Such information is necessary to apply the percolation theory to the flame spread among randomly distributed droplet clouds. The on-orbit experiment consists of the three kinds of different experiments, while all experiments use n-decane as fuel. Regarding more detail on the on-orbit experiments, please refer to the literatures [1), 2)].

3. Experimental Apparatus

As the dedicated experimental apparatus for the experiment, Group Combustion Experiment Module (GCEM) was developed by JAXA. GCEM has multiple functions such as fuel droplets generation, ignition of a droplet, observation of the droplets and flame spread behavior, and gas supply and exhaust. The sub-systems of the GCEM include the Syringe Unit, the Digital Camera Unit, the High-Speed Camera Unit, the Power and Communication Control Unit, the Small Combustion Vessel and the Gas Bottles. In the Small Combustion Vessel, there are a SiC fiber lattice, igniters, a traverse mechanism, glass needles, and a soot removal unit. Schematic of the GCEM is shown in **Fig. 1**.

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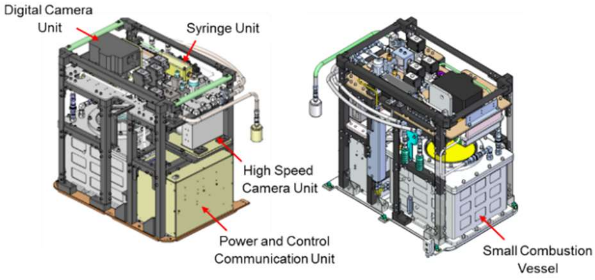

Fig. 1 Schematic of the GCEM.

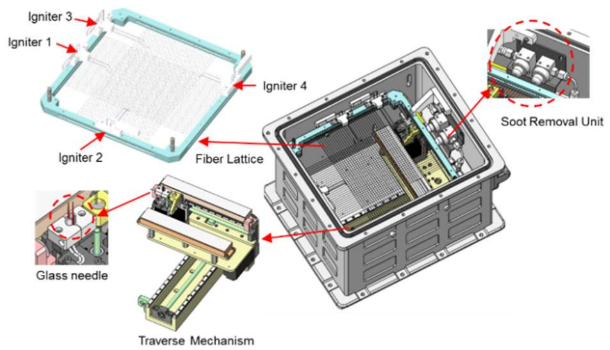

Fig. 2 Schematic of the components inside the Small Combustion Vessel.

The fuel used in this experiment is liquid n-decane ($C_{10}H_{22}$). Fuel droplets are generated either on the crossing points of the SiC fiber lattice (30 x 30, fiber diameter: 14 µm) or on a single SiC fiber (fiber diameter: 78 µm), depending on the experiment. A droplet, which is generated on the edge of SiC fiber lattice or a single SiC fiber, is ignited by the electrically heated wire. After ignition of the edge droplet, flame spreads to the neighboring droplets one after another.

All combustion experiments are performed inside the Small Combustion Vessel, a part of the pressure system. Combustion phenomena are observed by a digital camera and a high-speed camera through the observation window of the combustion vessel. Schematic of the components inside the Small Combustion Vessel is shown in **Fig. 2**.

For the on-orbit experiments, the GCEM is installed in the Chamber for Combustion Experiment (CCE), which is sub-system of the Multi-purpose Small Payload Rack (MSPR). Then, the CCE is set at the Work Volume (WV) of the MSPR. A Gas Bottle, in which high-pressure air is filled, is installed in the Small Experiment Area (SEA) of the MSPR. MSPR provides electrical power, ethernet lines, gas supply and waste lines to the GCEM through the CCE. Schematic of the installation procedure of the GCEM into the MSPR is shown in **Fig. 3**. More detail information on the GCEM can be available in the literatures [3), 4)].

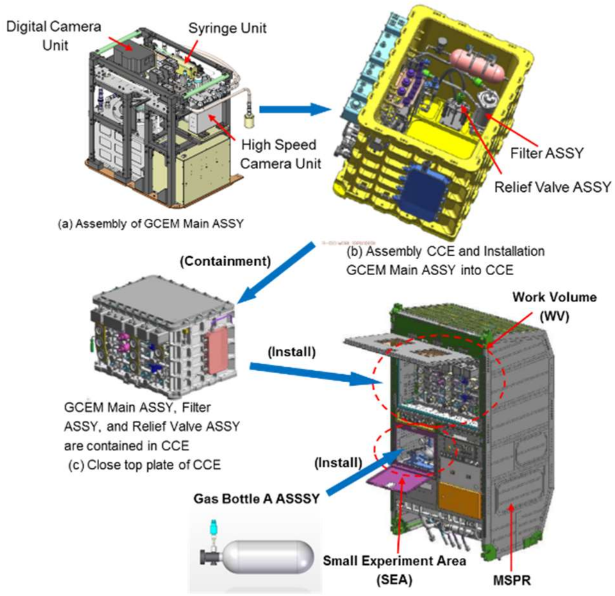

Fig. 3 Installation procedure of the GCEM into the MSPR.

4. Development of the GCEM

4.1 Development and Verifications of the Experimental Technique

In the GCEM, fuel droplets are generated either on the intersections of the SiC fibers or on a single SiC fiber, by supplying the fuel from a glass-tube needle through a teflon tube. Diameter of generated fuel droplets can be varied by the amount of supplied fuel, which is precisely controlled by the motion of the stepping motor in the Syringe Unit. This technique was originally developed by Mikami et al. for the short-duration microgravity experiments at the drop shaft [5)]. At early phase, the technique was applied to generation of a linear fuel droplet array. Then, the technique has been evolved to generate 2-D droplet clouds on the SiC fiber lattice. Similar technique on fuel droplets generation was demonstrated for the first time in the long-duration microgravity experiment at the sounding rocket experiment by the TEXUS 46 in 2009 [6)]. Also, the parabolic flight experiments were performed by using the bread board model (BBM) and the engineering model (EM) of the GCEM, for verification of the several critical experimental techniques and functions of the experimental apparatus in reduced gravity environment [3), 7)]. The results and findings in these precursory experiments and tests played an important role for the development of the GCEM.

4.2 Evaluation on Safety Aspects

In execution of any on-orbit experiments, safety evaluation is mandatory so that both experimental apparatus and the experiment itself do not cause damages to the flight crew, ISS and launch vehicle in each phase, including launch, storage, setup, experiment operation, close-out, and disposal. In accordance with the safety requirements, all possible causes to yield various hazards are identified for each experimental apparatus. Then, appropriate control methods that prevent or minimize each hazard are decided. Finally, the effectiveness of the control methods is verified through one or more approach of tests, analyses, inspections, and demonstrations.

For GCEM, multiple hazards were identified by the safety evaluation process. Here, control methods for two major hazards are briefly introduced on (1) Broken glass and (2) Fire.

(1) Broken glass

“Broken glass” is the hazard of contamination by floating cracked glass, and injury by broken glass. This hazard may be caused by vibration at launch phase and rupture in the experiment operation. For example, **Fig. 4** to **Fig. 6** show the configuration of the components that include glass part. The glass lens of the high-speed camera, the liquid crystal screen of the digital camera, and the fuel syringe which is made of glass are all covered by ziplock® material. Furthermore, each component is put inside a ziplock® bag. As a result, each component which has glass parts

Fig. 4 Launch configuration of the High-Speed Camera Unit ((C) JAXA).

Fig. 5 Launch configuration of the Digital Camera Unit ((C) JAXA).

Fig. 6 Launch configuration of the Syringe Unit is contained with double seal condition. In the orbit, the flight crew inspected these components prior to take them out from the bag ((C) JAXA).

(2) Fire

"Fire" is one of the catastrophic hazard that may be caused by overheat of electrical components, arc discharges, and so on. Various countermeasures are applied to prevent fire, since the flame is intentionally made inside the small combustion vessel of GCEM. For example, on the control of oxygen concentration, oxygen concentration inside the CCE was lowered during the operation of the GCEM. In the nominal environment, oxygen concentration inside CCE is 21 %, same as the ISS cabin ambient. There is a possibility that occurs fire inside the CCE, if GCEM has critical failures in such environment. According to the ISS safety requirements, however, it can be regarded that there is no risk of fire when ambient oxygen concentration is less than 10.5 %. To realize such condition inside the CCE, GN2, provided to GCEM through the MSPR gas supply line from the ISS, was injected in the CCE from the port of GCEM, to decrease oxygen concentration inside the CCE, at first. Next, the mixture of air and GN2 with elevated pressure inside the CCE was released into the cabin in the Kibo, by operating the manual valve of the CCE. As a result of these procedures, the gas mixture of oxygen and nitrogen with lowered oxygen concentration at 1 atm is produced inside the CCE. Repeating these procedures a few times made it possible to realize the atmosphere with less than 10.5 % oxygen concentration inside the CCE.

4.3 Ground Tests

In the test matrix of the on-orbit experiment, the number of the random droplets to be generated ranged from 81 to 152, depending on the condition. It takes several tens of minutes to generate such large number of fuel droplets on the SiC fiber lattice. If all droplets are generated in a same size, the size of each droplet at the timing of the combustion experiment would be varied each other, depending on the elapsed time after generation of each droplet, though n-decane is relatively less volatile fuel. Fuel droplets made in earlier timing would be advanced its vaporization, leading to smaller diameter after some time. Since the experiment required an uniform droplets diameter range within specific value at the ignition timing, optimization of the droplets diameter at the generation timing was necessary. In general, the droplets generated in earlier timing were made in much larger diameter than the nominal diameter for the combustion experiment, while the droplets generated in later timing were made in only a little bit larger than nominal diameter.

However, the droplets generation procedures mentioned above are not sufficient to make many droplets with uniform diameter. An additional factor to affect the vaporization rate of each droplet is interaction with the neighboring droplets. If there are many droplets around the specific droplet, the vaporization rate of the

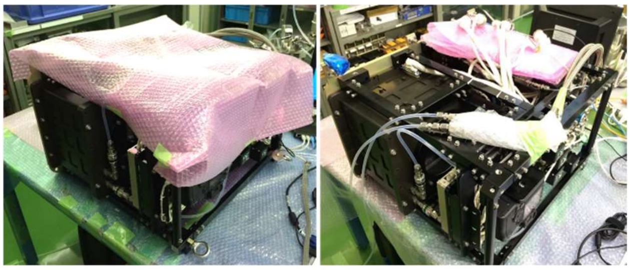

Fig. 7 Photo of GCEM PFM during the droplets generation test ((C) JAXA).

droplet is reduced than that in isolated condition, due to moderate gradient of fuel vapor concentration around the droplet. On the other hand, the vaporization rate of the droplet which has long distance with the neighboring droplets is almost same as that in isolated droplet. Since the arrangement of the droplets is decided to simulate the nature of the randomly distributed droplets, there are both dense and coarse region on the droplets distribution. On the ground, in addition, we also have to consider the effect of gravity. The density of fuel vapor is larger than that of air. Therefore, fuel vapor around the droplets tends to settle down to lower direction.

Considering all these effects, the efforts to optimize the droplets generation sequence were repeated on the ground by using the GCEM Proto Flight Model (PFM). In the tests, the GCEM PFM was laid down so that the plane of the SiC fiber lattice inside the small combustion vessel is vertical, as shown in **Fig. 7**. In order to measure the diameter of each droplet, the back-lit image of the droplet is employed. A white-color LED as the back light is installed on the traverse mechanism below the fiber lattice, as shown in **Fig. 2**. If the plane of the SiC fiber lattice is horizontal, it is difficult to measure the differences in diameter of each droplet, since the droplets deform in the direction of the optical path by gravity. Therefore, the GCEM was laid down to facilitate the measurement of droplet diameter, even in normal gravity.

After significant repeat of the tests, it became possible that more than 97 % of the generated droplets meet the acceptable dispersion. In addition to the droplet generation test, many tests were performed on the GCEM PFM on the ground. It includes functional test, pressure proof test, thermal-cycle test, fit check to the CCE, vibration test, noise test, EMC test, and off-gassing test.

4.4 Filling of Fuel

A big issue to handle liquid n-decane is the occurrence of air bubble. The fuel is contained in the Syringe Unit. If air bubbles occur in the syringe, the accuracy on the generated droplet diameter would be affected. Therefore, prevention of air bubbles inside the syringe unit is very important. For that, n-decane was degassed, and filled into the syringe in a vacuum environment.

Figure 8 shows the degassing equipment and the oxygen concentration sensor, used in the relevant works. The degassing equipment has functions to generate an ultrasonic wave and to exhaust gases. For degassing, n-decane is poured into a metal vessel that is connected to the ultrasonic generator and the exhaust equipment. Then, the fuel is degassed by the ultrasonic wave. After the degassing is completed, a top lid of the vessel is opened to measure the dissolved oxygen concentration in the fuel. The target criteria of the dissolved oxygen concentration is less than 1 ppm. If the measured result exceeded that criteria, same procedure was repeated until the result meets.

Figure 9 shows the fuel filling equipment that can fill n-decane into the syringe in a vacuum environment. The equipment consists of a stepping motor, fuel cup, ball screw, quick-disconnects (QD), fuel pipe, metal frame, pressure gauge and acrylic enclosure. The acrylic enclosure is connected to a vacuum pump.

The degassed n-decane is poured in the fuel cup, set on the bottom of the fuel filling equipment. The fuel is provided to the syringe through the fuel pipe. Then, the Syringe Unit is driven by the stepping motor and the ball screw, to fill n-decane into itself. During the filling operation, inside of the acrylic enclosure is kept as vacuum environment, so that gas dissolution in the n-decane is prevented.

Fig. 8 Photo of the degassing equipment ((C) JAXA).

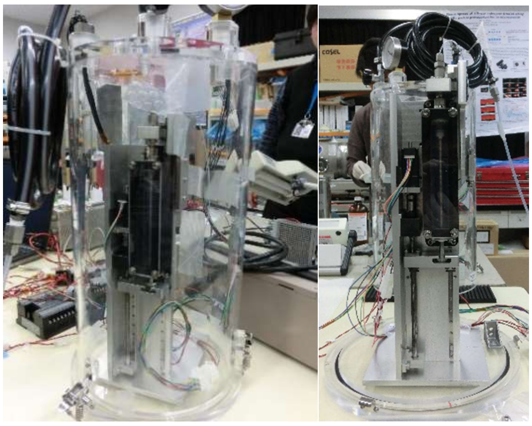

Fig. 9 Photo of the fuel filling equipment ((C) JAXA).

Fig. 10 Photo of the Gas Bottle ((C) JAXA).

Fig. 11 Photo on the gas filling operation at WFF ((C) NASA/JAXA).

4.5 Preparation of Gas Bottles

The Group Combustion experiment needs oxygen resources for combustion. Since the oxygen resources shall be prepared by ourselves, the Gas Bottles, as shown in **Fig. 10**, were developed based on the existing gas bottle used for the Kibo system.

The big issue on the high-pressure gas bottles is their ground transportation. High-pressure gas bottles are designed and manufactured in accordance with the relevant law in each country. Therefore, the gas bottles are allowed to transport on the ground in the manufacturing country.

The gas bottles for GCEM is manufactured in Japan in accordance with the KHK standard (Japanese high-pressure gas standard). Therefore, transportation of the gas bottles is allowed only in Japan, when high-pressure gas is filled. However, there was a possibility that the gas bottles shall be launched by U.S. vehicle (DRAGON or CYGNUS), depending on the launch schedule of the vehicles. For launch of the gas bottles by the U.S. vehicle, the gas bottles shall be transported to U.S. from Japan. However, the gas bottles are not allowed to transport in U.S. when high-pressure gas is filled, since the bottles are not manufactured in accordance with the DOT standard (U.S. high-pressure gas standard). In addition, the high-pressure gas bottles are not allowed to transport on airplanes.

For these reasons, we considered the possibility to perform the gas filling operation in the launch site. Through discussion with the Mission Integration and Operations Office in NASA Johnson Space Center (JSC), it turned out that Wallops Flight Facility (WFF) in Wallops, Virginia was the most promising launch site to execute gas filling operation. From the WFF, CYGNUS cargo craft of the Orbital Sciences Corporation (OSC) is launched by the ANTARES rocket. Coordination with JSC, WFF, and OSC was performed mainly by e-mail and telecon. In addition, we actually visited WFF to have a technical interchange meeting (TIM) one time. There were many technical issues for preparing the gas filling operation. However, our joint Japan-U.S. team cleared such issues one by one, since all people of JSC, WFF, and OSC were very supportive. Finally, we completed the preparation to execute the gas filling operation at the WFF, by the autumn in 2014. We've just performed a trial gas filling to one of the GCEM gas bottles in the WFF at this time and waited the final decision of the launch vehicle of the GCEM gas bottles.

Unfortunately, however, the accident occurred in the launch phase of the OA-3 (CYGNUS No.3) in October 2014. The OA-3 exploded just after it was launched from the launch pad of the WFF. This accident caused serious damage to the launch pad. Also, launch of the CYGNUS cargo craft by the ANTARES rocket was suspended until the investigation on the causes of the accident was completed. As a result, after the OA-3 accident, it was decided to launch the GCEM gas bottles by the H-II Transfer Vehicle (HTV) from Japan. All GCEM gas bottles, transported to the WFF, were shipped back to JAXA after high-pressure air was released at the WFF.

Actual gas filling to the gas bottles for launch was not performed at the WFF for the Group Combustion experiment. However, technical procedures on the gas filling at the WFF, established through the Group Combustion experiment are novel for future experiments. In fact, gas filling at the WFF was performed for other experiment after a few year later (see **Fig. 11**), and the bottles were launched from the WFF by the ANTARES rocket.

4.6 Launch of GCEM

Launch of the GCEM components were divided into a few launch vehicles, since it was difficult to secure the space to accommodate all components in one vehicle. First launch of the GCEM component was the SpaceX's DRAGON cargo craft to be launched by the FALCON rocket from Cape Canaveral, Florida. The Digital Camera Unit and the High-Speed Camera Unit of GCEM were installed in the SpX-7 (DRAGON No.7). The SpX-7 was launched in June 2015. However, it disintegrated 139 seconds into the flight after launch, just before the first stage was to separate from the second stage. By this accident, both the Digital Camera Unit and the High-Speed Camera Unit were lost. Fortunately, there was a spare for the both units on the ground, which have same specifications as the lost PFM units. Preparation

Fig. 12 Photo on the Launch of the HTV-5 ((C) JAXA).

of the spare camera units to launch was started just after the SpX-7 accident. In parallel, new spare set of the camera units was procured and prepared to be in readiness for additional unexpected accidents. The new Digital Camera unit and the High-Speed Camera Unit were successfully launched by the SpX-9 (DRAGON No.9) in July 2016, as a result.

The remaining components of the GCEM, including the Gas Bottles, were launched by the HTV-5 in August 2015 from the JAXA Tanegashima Space Center, as shown in **Fig. 12**.

5. On-orbit Operation of the Experiment

5.1 Overview of the Experiment Operation

During the on-orbit experiment operation, UI (User Integration) team, consists of JAXA and associated companies, gathered with the investigators at the User Operation Area (UOA) in the JAXA Tsukuba Space Center. Since the Kibo is flying about 400 km above the ground, UI and the investigators have to operate the GCEM by remote control from the UOA. Also, the downlinked video images and telemetry data are monitored during the on-orbit operation at the UOA (**Fig. 13**). The role of the UI team is executing the on-orbit experiment, in cooperation with the Kibo flight control team of JAXA and the investigators. The UI team requests transmission of the operating commands to the GCEM to the MSPR rack officer and operators. The operating commands are delivered in a few seconds to the GCEM via the ISS and the MSPR. Also, the UI team monitors and judges the progress of the experiment operation, in discussion with the investigators.

Fig.13 UI team monitoring the downlinked video images and telemetry data at the UOA ((C) JAXA).

The on-orbit experiment operation consists of the three phases: checkout phase, experiment phase, and closeout phase. In the checkout phase, installation, initial function check, droplets vaporization test, and ignition test were conducted. Installation and initial function check of the GCEM were conducted without the investigators since no experimental judgement is included. On the other hand, the investigators participated in the droplets vaporization test and ignition test. Since n-decane droplets vaporize during the droplet generation, the expected droplet diameter after some time is calculated based on the vaporization rate of the droplet. Regarding the vaporization rate of n-decane droplet at room temperature in microgravity environment, only limited data were available, which have been obtained by the ground-based short duration microgravity experiments.

However, reliable vaporization rate in microgravity environment can be obtained only by the measurement in long duration microgravity environment. Therefore, measurement of the vaporization rate of n-decane droplet was performed at early phase of the on-orbit experiment. In the droplets vaporization test, the vaporization rate of both single droplet and two interacting droplets was measured over 3,000 seconds. Such long-time observation on the vaporization of fuel droplets in microgravity is the first achievement in the world, though the physical system is simple. The vaporization coefficient of n-decane was corrected by using the results of such preliminary tests before the actual combustion experiments. Detail on the droplets vaporization experiment can be shown in the literature [8].

In the experiment phase, both the UI team and the investigators attended the experiment operation. Downlinked experiment data were immediately transferred to the ground support system of the GCEM which was set at the UOA for quick analysis. Experimental data was also transferred to the investigators by using an authorized secure server. It enabled quick evaluation of the experimental results and decision on the subsequent experiments even the investigators are not participating the operation in Tsukuba.

In the closeout phase, uninstallation of the GCEM/CCE from the MSPR was conducted by the flight crew, in cooperation with the ground support team.

5.2 Success of the First Combustion Experiment in Kibo

The Group Combustion experiment in Kibo was started in September 2016, after arrival of all GCEM components to the

Kibo on July 2016. In the checkout phase, at first, the installation of the GCEM was successfully conducted by JAXA astronaut Takuya Onishi. The installation work included assembly of some components to the GCEM main body. The Syringe Unit, the Digital Camera Unit, and the High-Speed Camera Unit, which were launched in separate configurations, were mounted to the GCEM main body. Also, the exhaust gas filter unit was installed in the CCE. Then, the GCEM was installed inside the CCE. Next, the CCE was installed at the WV of the MSPR. In addition, a Gas Bottle was mounted in the SEA. The installation task was completed by connecting all cables and plumbing. Although these works are very complicated, astronaut Onishi, with partial support by another flight crew, carefully performed all works within the expected crew time. The photo of him in front of the MSPR/CCE after completion of the installation task is shown in **Fig. 14**.

During the early phase of the initial function check, air leak from the air supply line of the GCEM was found. The countermeasure to the air leak is described in detail in 5.3. After the problem is solved, the remaining function check was resumed. Then, droplets vaporization tests, briefly described in 5.1, were executed. Following the droplet vaporization tests with single or a few droplets, large-scale droplet clouds with 97 droplets were made. Based on the results of the first trial generation, droplets generation profile was further corrected to improve the uniformity of the droplets diameter at when all droplets are generated. Finally, almost all of 97 droplets were successfully generated within 1 ± 0.05 mm in diameter. **Fig 15** shows the actual result of generated droplets size for 97 droplets.

At the end of the checkout phase, ignition test of droplet was performed. After the ignition test for a single droplet, randomly distributed 97 droplets were generated and ignited. Investigators and the UI team gathered in the UOA and carefully monitored the progress of the experiment operation. Though telemetry data on temperature and pressure suggested the success of combustion, the video image can be only seen after a few minutes. The atmosphere in the UOA was filled with expectation and anxiety during the video data downlink. As soon as the downlinked video was replayed, everybody shouted for joy because the video clearly showed the success of the flame spread among randomly distributed droplet clouds, which is also the first achievement in the world (see **Fig. 16** and **Fig. 17**).

Fig. 14 Photo of astronaut Onishi in front of the MSPR/CCE after completion of the installation task ((C) JAXA).

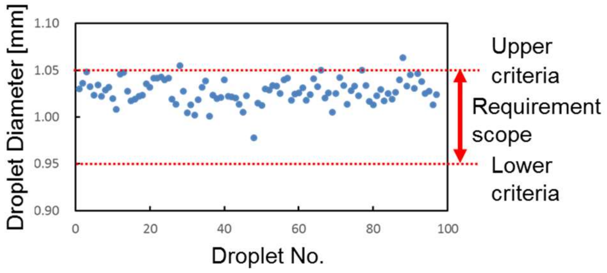

Fig. 15 Droplets size after generation of all 97 droplets (On-orbit) ((C) JAXA/Yamaguchi Univ.).

Fig. 16 Principal Investigator, Prof. Mikami, and Dr. Kikuchi of JAXA are shaking hands with celebrating the success of the first flame spread experiment among randomly distributed droplet clouds in Kibo ((C) JAXA/Yamaguchi Univ.).

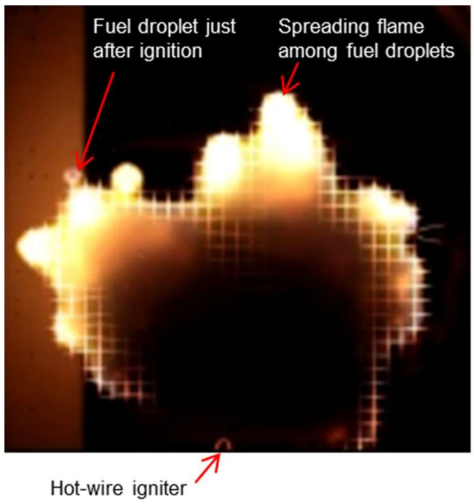

Fig. 17 Image on the first flame spread among randomly distributed n-decane clouds in the on-orbit experiment. The number of droplets is 97 ((C) Yamaguchi Univ./JAXA).

In the experiment phase, as many as 153 test matrixes were conducted in total. During the on-orbit experiment, many interesting data were acquired. Also, several unexpected phenomena were observed. Therefore, experiments to investigate such phenomena with new or modified test conditions were also performed in addition to the planned test matrixes.

GCEM was designed so that experimental parameters, such as droplet generation pattern, observation condition, could be easily changed by modifying the sequence file. The droplet generation pattern files were stowed in the Power and Communication Control Unit of the GCEM. Also, GCEM was controlled by the embedded Windows® OS. Therefore, GCEM had remote desktop function. Also, ground crews were able to use Ku bidirectional communication terminal as the experiment operation environment. By using this function, we were able to access into the GCEM for changing and making the droplet pattern file directly. Such flexibility of the GCEM greatly contributed to the successful operation.

After the on-orbit operation about 10 months, the GCEM and the CCE were uninstalled from the MSPR in July 2017, resulting in the acquisition of experimental data that are beyond expectation.

5.3 Countermeasures to Technical Issues Occurred during the Experiment

(1) Air leakage

In the checkout phase, air leakage was found at the Oxygen Gas Supply line. Since there were several suspicious leak points, we tried to identify the leakage region by the leak tests with different configurations. After the tests, it turned out that the leakage point is located in the GCEM air supply line, instead of the CCE gas line nor the interface QD between the CCE and the GCEM (see **Fig. 18**). We asked the flight crew to tighten up some fitting in the line and re-performed the leak test. However, the leakage was never improved.

At the time, we considered 2 methods to respond to this trouble. One method is exchanging gas supply line, and the another is to keep operation of the GCEM with accepting the air leak. Fortunately, the leak rate was estimated to be very small based on the ever leak tests data. However, to minimize the air leak during the operation, it was necessary for the flight crew to operate the manual valve for every air supply operation, though necessary crew time for each operation is less than 10 minutes.

The spare air supply line of GCEM did not exist at that time. Also, it was estimated that it takes more than a few months to prepare the spare air supply line. In addition, there was a concern that the exchanging operation of the air supply line by the flight crew causes additional damage to the other part of the GCEM. As a result of the trade-off on these situations, it was decided that the operation of the GCEM is continued with the air leak. To reach this decision, many discussions and considerations were made with the safety & mission assurance sections in JAXA and NASA, increment managers, the Kibo flight control team, and other relevant people.

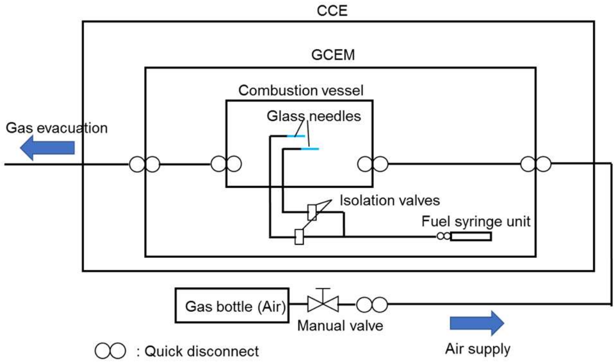

Fig. 18 Schematic on the fluid system lines (simplified) of GCEM and CCE.

This decision was the important turning point on the on-orbit operation of the GCEM. It should be noted that the final success of the Group Combustion experiment is significantly owing to this decision.

(2) Increase of fuel consumption

During experiment operation, n-decane shall be filled to the tip of the glass needle for the appropriate generation of fuel droplets. So, an initialization process is necessary to perform the droplets generation since the fuel surface moves back inside the glass needle due to vaporization after the previous operation. The fuel initialization was performed at the start of every experiment. This initialization method is performed by pushing the plunger of the fuel syringe a few times by the stepping motor to supply fuel till the tip of the glass needle.

In the experiment operation, however, it was observed that it takes much more pushes to supply the fuel to the tip in the first-time initialization in each day. It seemed that the fuel loss from the glass needle tip was significantly accelerated than usual by some reason. After careful evaluation of the relevant procedures, long term (about 10 to 60 minutes) vacuum environment inside the small combustion vessel, which became necessary due to adoption of the leak acceptable operation, was considered to be the reason (see **Fig. 18**). In the leak acceptable operation, operation of the manual valve at a certain timing shall be performed by the flight crew so that the amount of air leak is minimized. Such operation was performed during the morning meeting in the orbit (evening in the Japan time) after the flight crew waked up. In the meeting, the flight crews and the ground crews participate to confirm the task plan of the day. By this meeting, we had to complete the operation of moving back of the fuel surface and closing an solenoid isolation valve. In the air leak acceptable operation, it was decided that the flight crew operates the manual valve just after the morning meeting. So, we had to wait the crew by that time as the small combustion vessel is kept

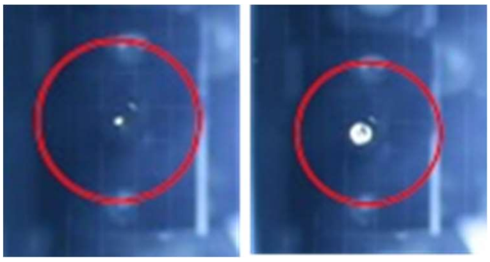

Fig. 19 Images of the sucked n-decane from the glass needle tip in the vacuum environment ((C) JAXA/Yamaguchi Univ.).

being evacuated. The waiting time depended on the progress of the meeting and differed day by day.

To confirm the reason of the increased loss of the fuel, the glass needle tip in the vacuum environment was observed. It showed that the n-decane was continuously sucked from the glass needle tip in the vacuum environment as shown in **Fig. 19**.

As the countermeasure to this problem, we tried to move back of n-decane inside the fuel tube until the upstream isolation valve before the combustion vessel is evacuated. By this, we expected that n-decane was prevented from being sucked out of the glass needle tip even in the vacuum environment. The result of trial operation was as expected. Therefore, this new operation was adopted in the subsequent experiment operation.

(3) Soot adhesion to SiC fiber

Soot generation was expected by the combustion of n-decane droplets. To remove soot from the SiC fibers, the soot removal unit was installed inside the small combustion vessel. The soot removal unit injects GN2 from its nozzle to the SiC fibers.

However, the amount of soot generation in the on-orbit experiment was much more than the expectations in advance. Also, some soot adhered to the SiC fibers and it remained even after GN2 was injected onto the fibers. If soot is remained around the intersection of the SiC fibers, the generated n-decane droplet on the intersection tends to shift to some direction as shown in the left image of **Fig. 20**. It causes the disorder on the droplets arrangements. It was also observed that the droplets generated side by side on a single SiC fiber sometimes merged into one large droplet, as shown in the right image of **Fig. 20**.

(Left) droplets shifted from the cross points of the SiC fibers.
(Right) 2 droplets merged into 1 large droplet on a SiC fiber.

Fig. 20 Images of soot adhered to the SiC fibers ((C) JAXA/Yamaguchi Univ.).

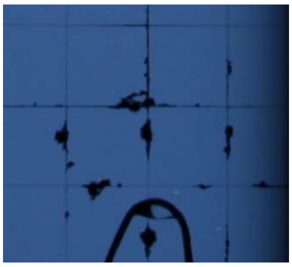

Fig. 21 A droplet adhered to the igniter-1 ((C) JAXA/Yamaguchi Univ.).

To remove such sticky soot, burning of the sooty region by generating a flame, adjacent to that region, was tried. Sometimes it successfully removed the target soot to a considerable extent, though this approach was not perfect. For some test conditions, the droplets had to be generated on the different area of the fibers instead of the planned area, to avoid the effects of soot, as described in (5) in detail.

(4) Failure on the igniters

GCEM has 4 igniters for three kinds of experiment. Igniter-1 and -2 are for the Experiment-1, igniter-3 is for the Experiment-2 (straight fiber) and igniter-4 is for the Experiment-3. In the on-orbit experiment operation, deformation and rupture of igniters were observed. For example, the shape of the igniter-1 gradually deformed with elongation by the accumulation of droplet ignition. Finally, when the droplet with 1.0 mm diameter, nominal size for the ignition droplet, was generated at the ignition position, the droplet adhered to the igniter-1 as shown in **Fig. 21**, since the distance between the igniter and the droplet became too close.

It is known that heating of the igniter in such condition may cause disruptive burning of the droplet. In the worst case, the igniter may be broken. Therefore, the diameter for the ignition droplet was changed to 0.9 mm to prevent its adhesion to the igniter in the subsequent experiment operation.

In the development of the GCEM igniters, the endurance test was performed. The igniters with the current specifications and heating profile passed the heating tests with a few hundred times. Also, actual ignition test of n-decane droplet was performed a few times for the igniters as PFM. Considering the troubles in the on-orbit experiment, however, durability of the igniters was not sufficient for the repetition of n-decane droplet ignition in microgravity environment. For ignition of n-decane droplet in microgravity, relatively large-diameter initial flame is formed around the droplet, comparing ignition in normal gravity. Therefore, not only the tip of the igniter, but also the whole igniter is surrounded by the initial flame. Increased thermal input to the igniter from the larger flame may be the major reason of such deformation of the igniters.

Also, the igniter-2 was broken after 64 times repetition of energization, as shown in **Fig. 22**. For the subsequent test conditions to use the igniter-2, the droplets arrangement on the

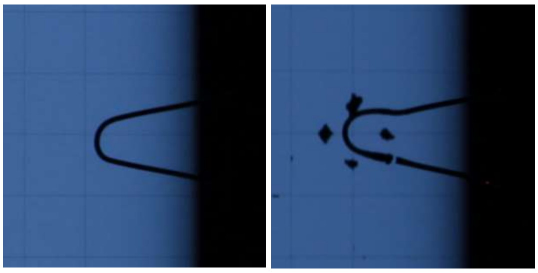

Fig. 22 Photo of the igniter-2 ((C) JAXA/Yamaguchi Univ.).

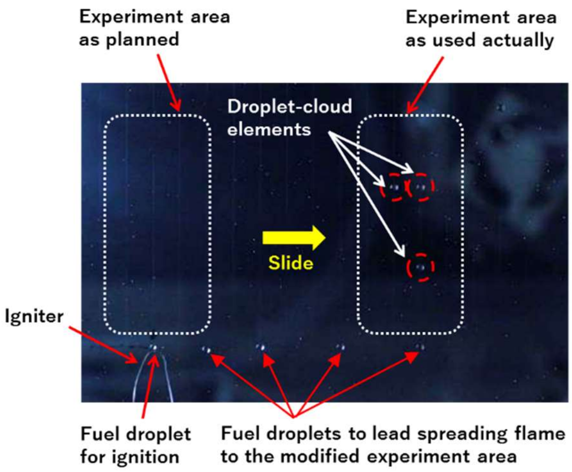

Fig. 23 Example of the modification of droplets arrangements ((C) JAXA/Yamaguchi Univ.).

SiC fibers were modified to use the other igniter, as described in (5) in detail.

(5) Droplets pattern change

As described in (3), it became difficult to use some area of the SiC fibers, due to adhesion of soot. Also, the igniter-2 was broken during the experiment, as described in (4). Therefore, modification of the droplet arrangements was necessary to use the different area of SiC fiber lattice and to use different igniter, as shown in **Fig. 23**. The droplet pattern files in the GCEM were changed to execute this modification.

6. Summary

The experimental data obtained by the on-orbit experiment have been analyzed by the investigators team. Papers on the on-orbit experimental results have been already published in the scientific journals [9), 10)]. Also, new proposal of the on-orbit experiment to reuse the GCEM, named the Group Combustion-2, was recently selected as a feasibility study experiment by JAXA[11)]. It is planned that unexpected phenomena, observed in the Group Combustion experiment, are further investigated in the new experiment.

Many technical considerations were necessary to develop the GCEM, since it is the first JAXA apparatus for combustion experiment in the ISS. As "fire" is regarded as the catastrophic hazard in the ISS, there needs careful consideration, evaluation, and design to handle real flame onboard the ISS/Kibo. In addition to the examples written in this paper, lots of technical concerns were cleared to execute the experiment in the Kibo, by the efforts of relevant people. It should be noted that technical achievement of the GCEM was commended by the Combustion Society of Japan, as the Technology Award in 2017[12)].

In the on-orbit operation, several technical issues occurred, as briefly introduced in this paper. Such experiences and findings are novel for the other experiments in the future. At present, development of the Solid Combustion Experiment Module (SCEM) and the Low-speed Low Lewis-number Premixed Counterflow Flame Equipment (L3-PO) are on-going in JAXA, for the upcoming on-orbit experiments in the Kibo. We will certainly take over the legacy, obtained in the Group Combustion experiment, to these experiments.

Acknowledgments

The authors would like to thank all people who participated in or supported the Group Combustion experiment. Mr. Y. Hisashi, Mr. Y. Sato, Mr. M. Nokura, Mr. Y. Goto, Mr. N. Hanafusa, and Mr. S. Yamamoto of the IHI Inspection & Instrumentation Co., Ltd. (IIC) contributed to the development of the GCEM. Ms. N. Sakurai and Mr. T. Shimaoka of the Japan Space Forum (JSF) contributed to the preparation of the experimental plan. Mr. T. Mizuno, Mr. K. Mitsumatsu and Mr. T. Sone of the Japan Manned Space Systems Corporation (JAMSS) supported the preparation of the on-orbit operation plan. Mr. S. Fukuyama of the Advanced Engineering Services Co., Ltd. (AES) contributed to preliminary ground tests. Also, JAXA Flight Control Team (JFCT) and JAXA Payload Flight Control Team (PL FCT) supported the preparation and real-time operation of the on-orbit experiment.

References

1) M. Mikami: J. of the Combust. Soci. of Japan, **56** (2014) 101.
2) M. Mikami, M. Kikuchi, Y. Kan, T. Seo, H. Nomura, Y. Suganuma, O. Moriue and D.L. Dietrich: Int. J. Microgravity Sci. Appl., **33** (2016) 330208.
3) M. Kikuchi and Y. Kan: Int. J. Microgravity Sci. Appl., **31** (2014) 78.
4) M. Kikuchi, Y. Kan, A. Tazaki, S. Yamamoto, M. Nokura, N. Hanafusa, Y. Hisashi, O. Moriue, H. Nomura and M. Mikami; Trans. JSASS Aerospace Tech. Jpn., **12** (2014) 25.
5) M. Mikami, H. Oyagi, N. Kojima, M. Kikuchi, Y. Wakashima and S. Yoda: Combust. Flame, **141** (2005) 241.
6) 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: Proc. 20th ESA Symposium on European Rocket and Balloon Programmes and Related Research, (2011) 473.
7) Y. Yoshida, N. Sano, T. Seo, M. Mikami, O. Moriue, Y. Kan and M. Kikuchi: Int. J. Microgravity Sci. Appl., **35** (2018) 350203.

8) M. Mikami, H. Nomura, Y. Suganuma, M. Kikuchi, T. Suzuki and M. Nokura: Int. J. Microgravity Sci. Appl., **35** (2018) 350202.
9) M. Mikami, Y. Yoshida, T. Seo, T. Sakashita, M. Kikuchi, T. Suzuki, and M. Nokura: Microgravity Sci. Tech., **30** (2018) 535.
10) Y. Yoshida, K. Iwai, K. Nagata, T. Seo, M. Mikami, O. Moriue, T. Sakashita, M. Kikuchi, T. Suzuki and M. Nokura, Proc. Combust. Inst., **37** (2019) 3409.
11) http://iss.jaxa.jp/kiboexp/news/2018_select.html
12) http://iss.jaxa.jp/kiboexp/news/gcem_171212.html