JAPAN-EUROPE COLLABORATIVE DROPLET ARRAY COMBUSTION EXPERIMENT IN MICROGRAVITY ONBOARD TEXUS-46 -TECHNICAL ACHIEVEMENTS AND PRELIMINARY SCIENTIFIC RESULTS

Masao Kikuchi[(1)], Shin Yamamoto[(1)], Shinichi Yoda[(1)], Masato Mikami[(2)], Hiroshi Nomura[(3)], Osamu Moriue[(4)], Akira Umemura[(5)], Yasuyuki Hisashi[(6)], Nobuhiro Sugano[(6)], Klaus Moesl[(7)], Thomas Sattelmayer[(7)], Christian Eigenbrod[(8)], and Olivier Minster[(9)]

[(1)]Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba, Ibaraki, 305-8505 Japan,
Email:kikuchi.masao@jaxa.jp
[(2)]Yamaguchi University, 2-16-1 Tokiwadai,Ube, Yamaguchi, 755-8611 Japan
[(3)]Nihon University, 1-2-1 Izumi-cho, Narashino, Chiba, 275-8575 Japan
[(4)] Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395 Japan
[(5)] Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603 Japan
[(6)] IHI Scube Co., Ltd., 1-22-17, Akebono-cho, Tachikawa, Tokyo 190-0012 Japan
[(7)] Technical University Munich, Boltzmannstrasse 15, Garching, 85748 Germany
[(8)] University of Bremen, Am Fallturm, Bremen, 28359 Germany
[(9)] European Space Agency, ESTEC, 2200 AG Noordwijk, Netherlands

ABSTRACT

A microgravity combustion experiment was performed on a partially pre-vaporized droplet array in November 2009, by the flight of TEXUS 46 sounding rocket, which was launched from the Esrange launch site in northern Sweden. The flight experiment was performed as a collaborative mission of JAXA and ESA. The Droplet Array Combustion Unit (DCU) was developed by JAXA and finally integrated as Japanese Combustion Module (JCM) to be installed into the TEXUS rocket. In the flight experiment, flame spread behavior of n-decane droplet arrays was observed with different degree of pre-vaporization. Also, collection of combustion gas samples during the flight was performed for gas composition analysis on the ground. In this paper, technical achievements of the DCU as well as preliminary scientific results are reported.

1. INTRODUCTION

The TEXUS 46 sounding rocket was launched on November 22, 2009, from the Esrange launch site in northern Sweden. In the flight of TEXUS 46, the combustion experiment of fuel droplet array was performed in microgravity environment, as the cooperative mission between JAXA (Japan Aerospace Exploration Agency) and ESA (European Space Agency). In this paper, technical achievements of the DCU, including a new technique for droplet generation and deployment, are reported. Also, preliminary scientific results of the flight experiments are reported, focusing on changes in flame spread phenomena depending on the degree of pre-vaporization.

2. OVERVIEW OF THE COLLABORATIVE MISSION

2.1. Project overview

The JAXA-ESA collaborative mission, reported in this paper, was executed based on the agreement which was coordinated between JAXA and ESA. Each party performed various tasks according to the agreement. Primary roles in each party are as follows:

① JAXA prepares the experimental plan for the flight experiment, based on the science requirements of the international investigators team.
② JAXA develops and provides the experimental apparatus to be installed on the TEXUS rocket.
③ ESA performs integration and tests of the experimental module, mission operation at the launch site.
④ ESA provides opportunity for the flight experiment by TEXUS rocket.

2.2. Outline of the flight experiment

"PHOENIX (Investigation of partial pre-vaporization effects in high temperature on evolution of droplet array combustion and nitrogen oxides formation)" is the title of the JAXA-ESA collaborative mission. The objectives of the experiment are investigation of the partial pre-vaporization effects on flame spread characteristics along the fuel droplet array as well as on the composition of combustion gas. The concept of the experimental objectives is shown in Fig. 1.

Combustion phenomena of liquid fuel droplets accompanying partial pre-vaporization (partially pre-vaporized droplets) are interest of fundamental

Proc. '20th ESA Symposium on European Rocket and Balloon Programmes and Related Research'
Hyère, France, 22–26 May 2011 (ESA SP-700, October 2011)

combustion research. It has intermediate featuers of gaseous premixed combustion and non-premixed droplet combustion. Also, it has large relevance to practical combustion devices such as liquid fuel gas turbines and aero engines. Although many investigations have been performed on macroscopic fuel spray, there exists few investigation on how pre-vaporization affects on combustion characteristics of the partially pre-vaporized droplets.

Kikuchi et al. have performed investigations of flame spread mechanism of partially pre-vaporized droplet array by using short duration microgravity experiment obtained by drop shaft [1]. It is possible to generate symmetrical fuel vapor layer around the axis of the array in microgravity environment, in which natural convection is restrained. In our past research, it was found that changes of flame structure and increase in flame spread rate occur with progress of droplets pre-vaporization. However, it was difficult to perform flame spread experiment in experimental conditions with large degree of pre-vaporization, due to the limitation of microgravity duration by drop shaft experiment. In this flight experiment by TEXUS rocket, therefore, experimental data acquisition with large degree of pre-vaporization was intended. n-decane ($C_{10}H_{22}$) was employed as fuel in the flight experiment, same as our past research.

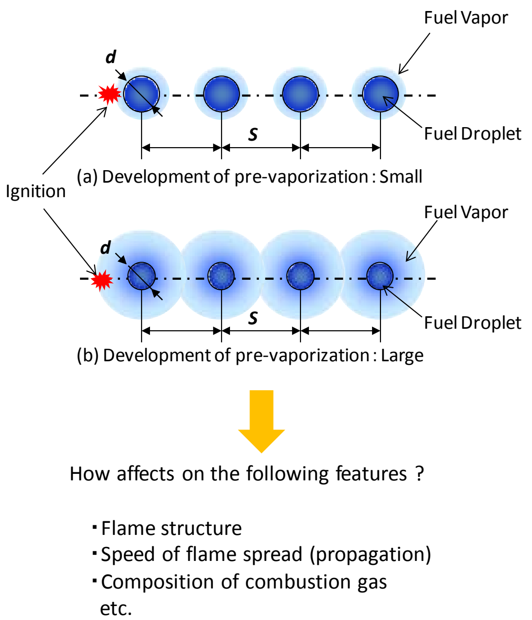


Fig. 1. Schematic of the objectives of the experiment.

For the flight experiment, the international investigators team containing Japanese and European investigators was established. In the collaborative mission, Japanese investigators focused on changes of flame spread characteristics with the degree of pre-vaporization. On the other hand, European investigators have interest in the effects of partial pre-vaporization on the gas composition, especially NOx (Nitrogen Oxides), in combustion gas. Therefore, not only observation of combustion phenomena in microgravity environment, collection of combustion gas samples during the flight experiment and subsequent gas composition analysis on the ground were also planned [2].

3. EXPERIMENTAL APPARATUS

3.1. Experimental module

Experimental modules flying on TEXUS is accommodated within a 438 mm diameter cylindrical payload envelope. In the scientific payload, max. 260 kg is allowed as the total mass of the multiple experimental modules. The Japanese Combustion Module (JCM) is developed and installed on the scientific payload of the TEXUS 46 for our combustion experiment. Experiment dedicated apparatus of the JCM is the Droplet Array Combustion Unit (DCU), developed by JAXA. The remaining devices of the JCM, including mechanical and electrical components, outer structures etc., has roles of interface with the TEXUS system. These devices are developed or procured by EADS Astrium under contract with JAXA. Picture of the JCM are shown in Fig. 2.

The height and weight of the JCM is 1290 mm and 103 kg, respectively. The DCU is upper part over the lowest circular plate (base plate) shown in Fig. 2 (a). The subsystems of the DCU are installed on the circular plates with 6 tiers. The DCU is consist of droplet array generation devices, droplet array holder, droplet array lifting device, combustion chamber, droplet array removal device, diagnostic devices, air supply system, exhaust gas sampling system (EGS), and main structure.

(a) (b) (c)

Fig. 2. Photo of the JCM ((a): without vacuum protection, (b): with vacuum protection, (c): final configuration with outer structure).

The combustion chamber is preheated prior to the launch, and keeps inner air temperature at 500 K. For each combustion run during the flight experiment, the droplet array lifting device inserts the droplet array holder into the combustion chamber through opened shutter at the bottom of the chamber. After insert of the droplet array into the chamber, pre-vaporization of the droplet array is made by some delay time on activation of the igniter at the edge of the array. The degree of pre-vaporization is controlled by the ignition waiting time t_w. An edge droplet of the array is observed and recorded by the onboard videocamera with a LED as backlight. This image is employed for measurement of initial droplet diameter which is inserted into the chamber. Also, time-dependent vaporization behaviors of the droplet, including calculation of the evaporation rate, are analized from the image. After ignition of the edge droplet, subsequent flame spread behaviors along the array are observed by a CCD video camera which is downlinked to the ground. Also, an onboard high speed video camera obtains flame spread images with 500 fps for measurement of flame spread/propagation speed. In addition, combustion gas after burning of the droplets is gathered for gas analysis on the ground. After the gas sampling procedure, the droplet array is lifted down and the shutter of the chamber is closed for venting of inner gas into outer space as well as subsequent refilling of fresh air into the chamber.

3.2. Experimental technique

A new technique for droplet generation and deployment was employed for the flight experiment. The technique has been already applied and demonstrated by drop shaft experiments [3]. However, the present flight experiment was the first opportunity to demonstrate the technique in space experiments. Droplet array holder and droplet array generation system are key apparatus.

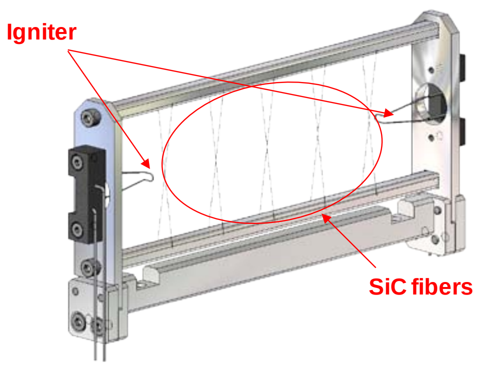


Fig. 3. Schematic of the droplet array holder.

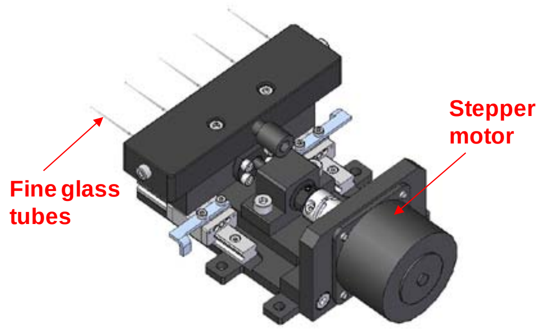


Fig. 4. Schematic of the droplet array generation device.

The droplet array holder is composed of two igniters and five sets of X-shaped SiC fibers with 14 micrometer diameter to support fuel droplets on intersections of the fibers, as shown in Fig. 3. Nominally, one igniter is used for ignition of the edge droplet. Another igniter is for redundancy purpose. Droplet array generation system generates droplets on intersections of SiC fibers by supplying fuel (n-decane) from the tips of fine glass tubes, as shown in Fig. 4. Droplet diameter, which is formed on the array holder, is controlled by the amount of fuel supply. Detail features of the new droplet generation technique are written in [3].

4. RESULTS OF THE FLIGHT EXPERIMENT

4.1. Flight summary

It was planned to perform totally 4 combustion runs in the flight experiment. Planned experimental conditions are shown in Tab. 1.

Table 1. Planned experimental conditions.

Experiment No.	d_0 (mm)	S (mm)	N	T (K)	t_w (s)
1	1.5	18	5	500	18
2	1.5	18	5	500	10
3	1.5	18	5	500	5
4	1.5	18	5	500	15

Droplet pre-vaporization time in 500K air before ignitor activation inside the combustion chamber, t_w, was primary experimental parameter in the flight experiment. Initial droplet diameter d_0, droplet interval S, the number of droplets in the array N, and ambient temperature of hot air inside the combustion chamber T are basically same for each runs, except experimental errors. Intended initial droplet diameter, d_0 = 1.5 mm, is relatively large compared with those employed in our past drop shaft experiments. The reason such large droplets are used is restraining deviations of development of fuel vapor around the droplets, which could be caused by experimental errors in d_0 and/or t_w. It was expected that each experimental condition corresponds to different situation regarding formation of flammable gas layer around the droplet array, according to the numerical simulations.

In the actual flight experiment, the 1st – 3rd combustion runs were performed as planned without any troubles. However, pressure indication of the air bottle suddenly decreased to “0” in short time during preparation of the 4th combustion run. As a result, devices operated by high pressure air such as air cylinder for the shutter of the combustion chamber became impossible to operate. In addition, the power of the JCM was shut down soon. Therefore, it was impossible to continue further experiment operation.

The reason of unintentional shut down of the JCM during the flight experiment was investigated by ESA and EADS Astrium after the flight. As a result, it was found that the timer sequence of the JCM started too early prior to lift-off, due to a delayed data indication on the GSE (Ground Support Equipment) display. Therefore, the timer sequence finished also earlier than planned. According to their investigation, different settings of the timing for the network communication in the operating system caused delays in the GSE display.

4.2. Generation of droplets

Generation of the droplet array on the SiC fibers was successfully performed for all 3 combustion runs. After confirmation of the droplet array generation on the GSE monitor, telecommand to initiate the combustion subsequence was transmitted to the JCM. The droplet array was lifted up into the combustion chamber by the subsequence. Example of backlit image of the lifted droplet is shown in Fig. 5. The observed droplet is an edge droplet of the array. Also, backlit droplet images at t = 0 (start of pre-vaporization) and $t = t_w$ (just before ignitor activation after the defined pre-vaporization duration) are shown in Fig. 6 (a) ~ (c) for 3 runs.

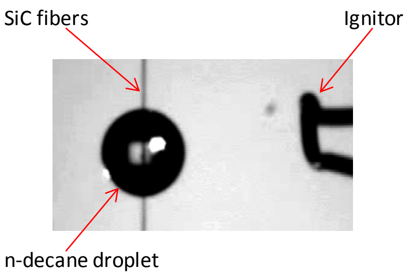
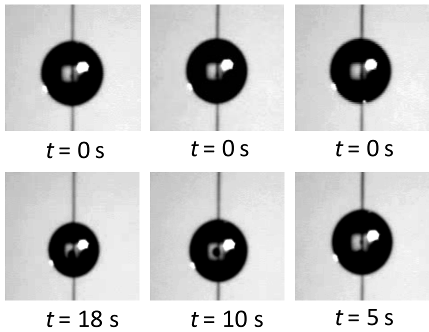


Fig. 5 Example of backlit image of the droplet.

Preliminary analysis of the initial droplet diameter (at t = 0 s) is shown in Tab. 2. It was found that generated droplets in each experimental run has high reproductivity. Detail calculation of the vaporization rate is on-going.



(a)1st run (b) 2nd run (c) 3rd run

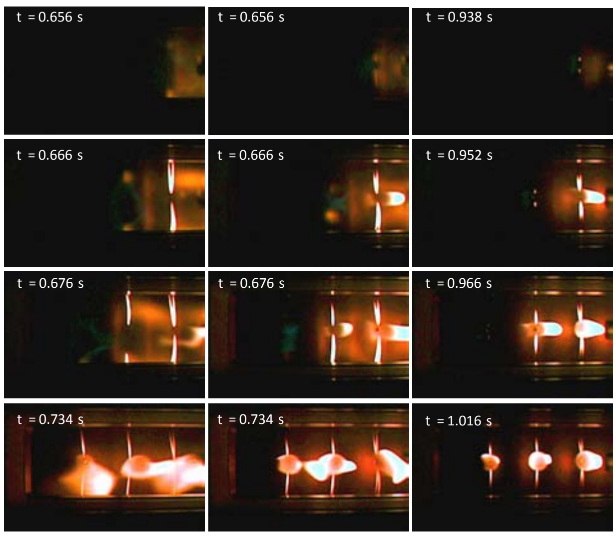
Fig. 6 Backlit droplet images at t = 0 and $t = t_w$ for 3 runs.

Table 2. Measured droplet diameter.

Experiment No.	d_0 (mm)
1	1.549
2	1.554
3	1.550

4.3. Flame spread along the droplet array

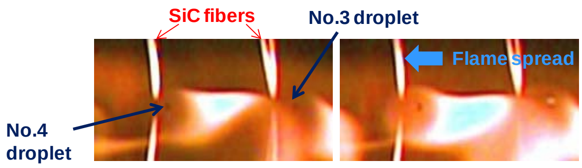
After pre-vaporization in the combustion chamber for t_w, an edge droplet of the array was ignited by the ignitor. Recording of the high speed video camera (HSV) was started at when ignitor was activated (t = 0). Sequential flame spread images of the HSV are shown in Fig. 7 (a) ~ (c) for 3 runs in the flight experiment. In Fig. 7, flame front travels from right to left side. Also, these HSV images cover the field of view containing from the 3rd droplet to the 5th droplet. The 1st droplet (ignited droplet) and the 2nd droplet are out of view in the HSV images.



(a) t_w = 18 s (b) t_w = 10 s (c) t_w = 5 s

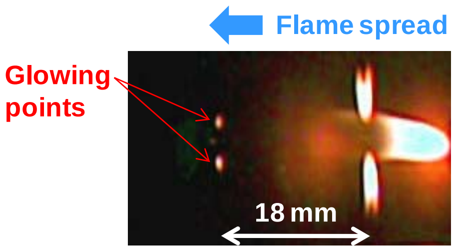
Fig. 7 Sequential flame spread images by high speed video camera.

In all cases, dim blue flame can be recognized at spreading flame front region. Following the blue flame region, luminous yellow flame can be seen. The shape of luminous flame around each droplet tends to change from wake flame at early phase to spherical envelope flame at later phase. The area of visible blue flame is larger for larger degree of pre-vaporization. On the other hand, brightness of blue flame for t_w = 18 s appears to be lower than the other conditions. Also, it was observed that the 3rd and 4th droplets detached from the intersections of SiC fibers during flame spread process for the 1st combustion run (t_w = 18 s) as shown in Fig. 8. The detachment would be attributed to strong gas expansion flow in the corresponding experimental condition.

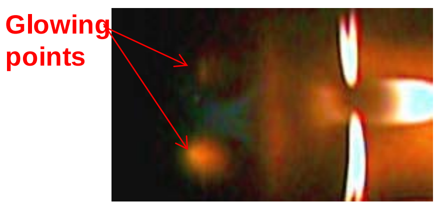


(a) t = 0.7 s *(b) t = 0.71 s*

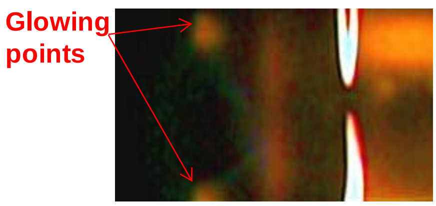
Fig. 8 Detachment of droplets during flame spread (t_w = 18 s).



(a) t_w = *5 s*



(b) t_w = *10 s*



(c) t_w = *18 s*

Fig. 9 Flame spread images at the moment of initial glowing of the SiC fibers for the 4th droplet.

In addition, it was observed that initial glowing point of each SiC fibers, when spreading flame front reaches to the fiber location, shifts outward with development of pre-vaporization of droplets as shown in Fig. 9. It shows the width of spreading flame front becomes larger with development of fuel vapor layer around the droplet array. Further analysis on flame spread phenomena is on-going.

4.4. Flame spread rate

Travelling speed of flame front, V_f, was tentatively calculated by using initial glowing timing of each SiC fibers. At first, V_f was calculated at each droplet interval (between the 3rd - 4th droplet and the 4th - 5th droplet) from the flame spread images. Then, averaged V_f was calculated from the 3rd to 5th droplet interval. The averaged V_f for each combustion run is shown in Tab. 3. In Tab. 3, similar V_f without little pre-vaporization (t_w = 0.1 s), which was obtained by our previous drop shaft experiments, is also shown as reference.

Table 3. Averaged flame spread rate as a function of pre-vaporization time (T = 500K)

Experiment No.	t_w (s)	V_f (mm/s)
1	18	1800
2	10	1650
3	5	1286
(Results of drop shaft exp.)	0.1	11

The experimental results show V_f basically increases with progress of pre-vaporization of droplets. Especially, it is obvious that pre-vaporization significantlly affects on V_f at relatively smaller t_w. Also, considering the measurement error of the experimental data, V_f with t_w = 10 s and 18 s have no or small difference. Therefore, it is suggested that V_f approaches a certain value at highly pre-vaporized condition. This trend of V_f could be reasonable since flammable gas layer around each droplet is merged at highly pre-vaporized conditions.

5. CONCLUSIONS

The JAXA-ESA collaborative combustion experiment “PHOENIX” was performed by the flight of TEXUS 46 in November 2009. The effects of partial pre-vaporization of fuel droplet array on flame spread and combustion phenomena were investigated. 3 combustion runs were nominally performed during about 6 minutes microgravity time, though the planned 4th run was not executed due to troubles in the GSE software.

A new technique for droplet generation and deployment was successfully demonstrated in space experiments at first. It was found that generated droplets in each experimental run has high reproductivity. Also, changes of flame spread phenomena depending on the degree of pre-vaporization are found. In addition, correlation of flame spread rate with degree of pre-vaporization was obtained.

Acknowledgments

The authors acknowledge all relevant parties to the project, including JAXA, ESA, SSC, IHI Scube, and EADS Astrium.

6. REFERENCES

1. Kikuchi, M., Sugano, N., Yoda, S. and Mikami, M.: Effects of pre-vaporization on flame spread of a linear fuel droplet array in microgravity, *Proceedings of the 6th Asia-Pacific Conference on Combustion*, 2007, pp. 639-642.

2. Moesl, K. G., Sattelmayer, T., Kikuchi, M. and Yoda, S.: Preparations of the NOx measurements for the combustion of an n-decane droplet array under microgravity conditions, *J. Jpn. Soc. Microgravity Appl*., Vol. 25, No. 3, 2008, pp.361-366.

3. Mikami, M., Oyagi, H., Kojima, N., Kikuchi, M., Wakashima, Y. and Yoda, S.: Microgravity experiments on flame spread along fuel-droplet arrays using a new droplet-generation technique, *Combust. Flame*, 141 (2005), pp.241-252.