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FLARE project における「きぼう」の微小重力環境を利用した低速気流中におけるろ紙上の燃え拡がり

Flame Spread on Filter Paper in Low-Velocity Ambient Flow Using the Microgravity Environment in KIBO on ISS in the FLARE project

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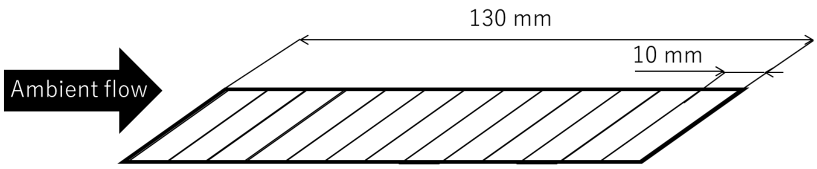
1. Introduction

To ensure fire safety in manned space activities, scientific standards and technical ground tests to evaluate fire hazardous characteristics of combustible solid materials in a microgravity field, are needed. The FLARE (Flammability Limits at Reduced Gravity Experiment) [1-4] is the project to establish the international fire safety standard for combustible materials under reduced gravity condition and based on Takahashi's scale analysis for opposed-flow flame spreading[5]. In the FLARE project, one of the primary tasks is to perform the solid combustion experiments on International Space Station (ISS) and to clarify the limiting oxygen concentration (LOC) for diffusion flames spreading over various solid samples with opposed and concurrent ambient flows. The limiting oxygen concentration indicates a critical value, below which flames cannot spread on flammable materials, and depends on the ambient flow velocity in both normal and micro gravity environments. For the opposed-flow flame spreading, the flame extinction characteristics and mechanism are mainly determined by heat transfers from the flame leading edge, that is, flame base, to the unburned material of the solid materials. On the other hand, in NASA's ground test method[5] for evaluating flammability of solid materials in a microgravity field, the flame spreads over the solid sample in the same direction as the ambient air flow. In the test method, preheating the unburnt region of solid materials by the flame and combustion gases cannot be avoided. As a result, the flame-extinction characteristics are strongly affected by both ignition and spreading processes in the upstream. From that point of view, it can be said that the FLARE test method that uses an opposed-flow flame spread is relatively simple and easy to understand the combustion phenomena and the experimental results. The Solid Combustion Experimental Module (SCEM)[3] for the FLARE project was launched and installed on the Japanese experiment module KIBO in the ISS, and the combustion experiments started in May 2022. Currently, the combustion experiments of a filter paper progress on ISS. In this report, we will show some of the on-orbit experimental results we have conducted so far. In particular, we will report on some results of the combustion experiments with a very low flow velocity and a long-time microgravity environment, which is the greatest advantage of on-orbit experiments.

2. Experimental setup and methods

The Solid Combustion Experiment Module (SCEM) was designed to obtain the limiting oxygen concentration for spreading flames formed over combustible solid materials placed in opposed and concurrent flows[1-3]. Also, it is possible to acquire the limiting electric current that self-ignition of the insulated wires. The detailed information on the structure and functions of SCEM is described in other literature and not explained here. There was a circulating wind tunnel in the SCEM and the initial oxygen concentration, pressure, and ambient flow velocity in the wind tunnel were provided precisely by the SCEM. Furthermore, the ambient flow velocity was possible to be pre-programmed to change the flow velocity to the desired value at each elapsed time after ignition. There were three color video cameras, one high-speed camera and one infrared camera in the SCEM. The green LED light was installed into the SCEM, and its luminosity could be varied. As the first microgravity combustion experiment using SCEM on ISS, a filter paper (Advantech 4A) was burnt. The filter paper had a thickness of 120 μm, an area density of 96 g/m^2. The sample width was 40 mm. Lines were drawn every 10 mm on the sample surface. Dimensions of the filter paper are shown in Fig. 1. For ignition, electrically heated wires were used and placed at both upstream and downstream sides of the sample. The value of electric current and the time for heating were variable. If the upstream end of the sample was ignited, a concurrent-flow flame spread was formed; if the ignition was ignited downstream, an opposed-flow flame spread was formed. The ignition wire was retractable and evacuated from the test section after ignition. In the wind tunnel, there were O_2 and CO_2 sensors and using these sensors we could know oxygen and carbon dioxide concentrations before and after the combustion experiment. In the next section of Results and Discussion, we will show the experimental result of the opposed-flow flame spread at very low velocity of ambient flow. This is one of the interesting results obtained from the experiments we have already conducted.



Filter paper (Advantec 4A, thickness: 120 mm, area density: 96 g/m^2)

3. Results and Discussion

3.1. Opposed-flow flame spreading on filter paper in a microgravity environment with change in ambient flow velocity

Figure 1 shows the sequential images of the flame spreading formed on the filter paper with a low-speed ambient flow velocity in a microgravity environment. The images were obtained from a camera looking down on the sample from the top. Ignition was performed at a current value of 6 A and its heating period was 10 s. The initial oxygen concentration was 21.07 vol.% and the oxygen concentration after the experiment was 20.89 vol.%. The initial temperature was 23°C and the initial pressure was 103 kPa. The flow velocity was varied as follows. At ignition, the ambient flow velocity was 2.6 cm/s. Then, 25 s after the start of the experiment, the flow velocity was changed to 2.1 cm/s. After 55 s, the flow velocity was changed to 1.3 cm/s, and then at 85 s, the flow velocity became 0 cm/s. This flow velocity condition is considered to be included in a radiation extinction regime in which flame extinction occurs due to radiative heat loss from the preheating zone of the filter paper to the surroundings. In each image, the time from the start of the experiment and the flow velocity conditions are shown. The ambient flow is provided from the left side of the image to the right.

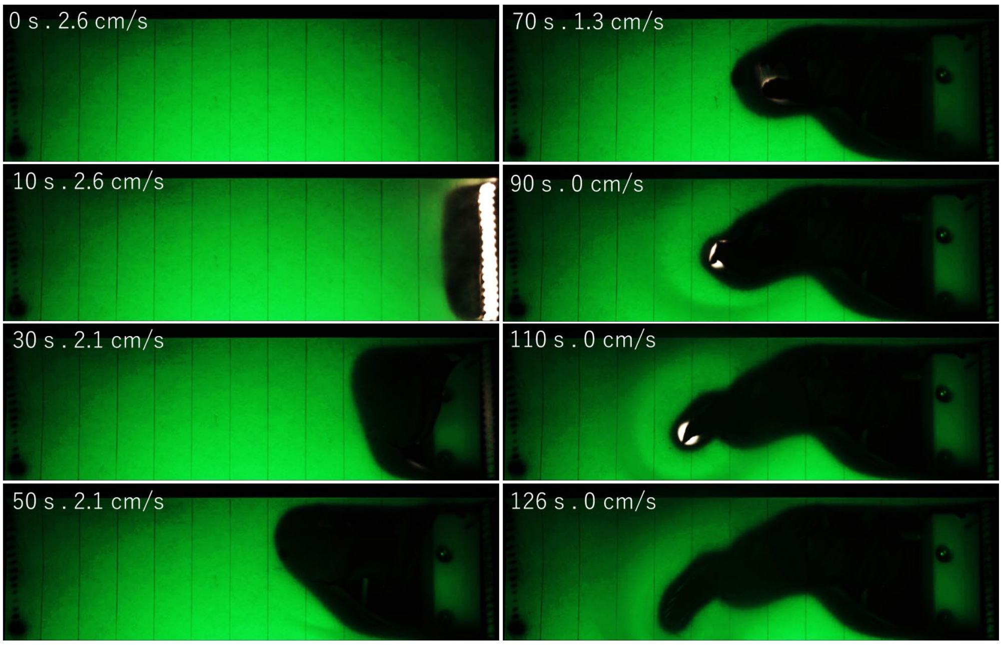


Figure 1. Sequential images of opposed-flow flame spreading formed over thermally thin filter paper in microgravity environment (initial oxygen concentration: 21 vol.%, flow velocity: 2.6 cm/s).

First, from the image at 10 s, it is found that a spreading flame with a two-dimensional flame structure was formed on the right edge of the filter paper. However, due to the weak luminescence from the diffusion flame and the camera's performance, it is difficult to see the reaction zone of the flame. On the other hand, the pyrolysis region where the filter paper turned black is clearly visible in the image. When the flow velocity changes to 2.1 m/s at 30 s, the pyrolysis region became a uniform shape in the width direction of the filter paper. At 70 seconds and a flow velocity of 1.3 cm/s, the flame did not have a two-dimensional flame structure but a three-dimensional one. At this time, the flame did not spread in a straight line. At 90 s, the flow velocity changes to zero, and although not visible in the image, the flame survived and continued to spread at very low flame spreading rate. The prediction based on the flame spreading on a combustible solid with a two-dimensional flame structure suggests that the flame could not keep the combustion reaction at zero velocity. However, from the experimental result, it is found that the flame is able to spread stably by changing the flame structure to a three-dimensional flame structure with curvature in its width. Finally, the flame advanced through the zero-velocity environment and its extinction occurred before consuming the entire filter paper. However, although later shown by thermal imaging, this extinction might have been caused by heat loss resulting from the flame zone contacting with the metal sample holder. In other words, if the width of the sample was larger, there is the possibility that the flame spread would have continued.

Basically, in a microgravity and quiescent environment, the oxygen transport to the combustion reaction zone in a gas phase is driven by its concentration gradient and the amount of oxygen supplied to the flame is thought to be not enough to continue the combustion reaction. In addition, the length of the preheat zone on the filter paper in front of the flame base becomes larger as the flow velocity decreases. As a result, the flame extinction is thought to be caused by radiative heat loss from the preheat zone on the filter paper[5)]. However, the present experimental result shows that flame can continue to spread on filter paper by changing from a two-dimensional flame structure to a three-dimensional flame structure even in a quiescent atmosphere. This is an important result in establishing fire safety in microgravity environments.

3.2. Infrared Image of spreading flame

Figure 2 shows the IR images of the flame spread shown in Fig. 1. The IR image provides information on the temperature distribution on the filter paper surface. The red area is the pyrolysis region which shows about 350°C, while the light blue area shows about 20°C. 10 s after the start of the experiment and at a flow velocity of 2.6 cm/s in Figure 2, the flame spread with a two-dimensional flame structure. Then, as the flow velocity is reduced, the width of the pyrolysis area decreases, and its shape changes to a circle one. From the IR image at a flow velocity of 0 cm/s, it is found that the diffusion flame increased spontaneously the flame surface area to maintain the supply of oxygen from the surroundings. In addition, it can be clearly seen that the length of the preheating region of unburned sample formed in front of the leading-edge flame increases. Furthermore, it is seen that the IR image at 110 s and 0 cm/s shows that a part of the flame zone interfered with the sample holder before the flame extinction occurred. This thermal interaction with the sample holder is thought to be one of the factors to cause the extinction in this experiment.

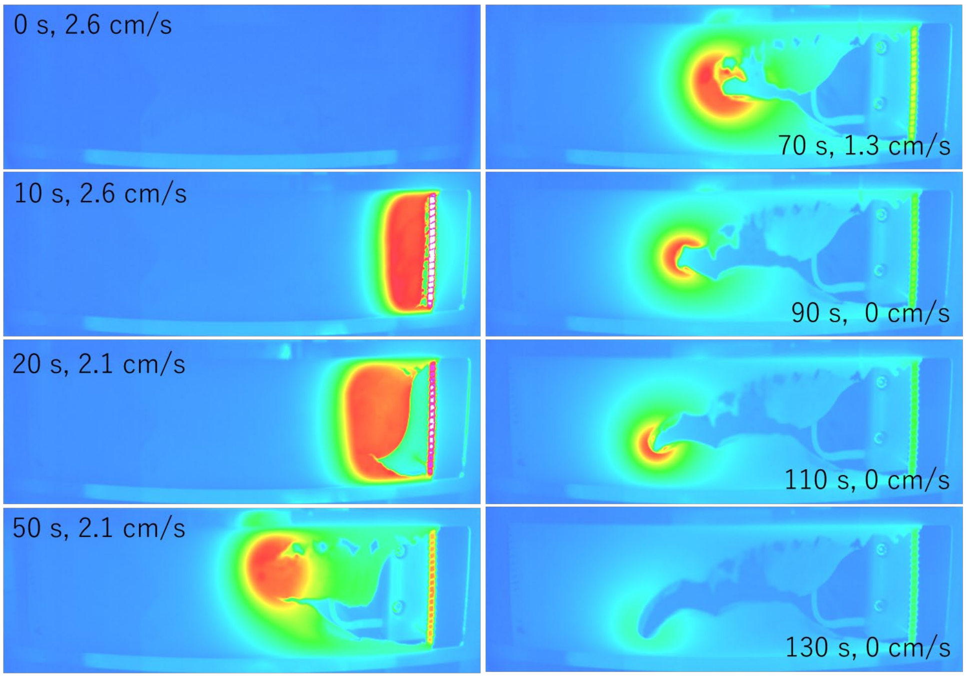


Figure 2. Sequential infrared images of opposed flow flame spreading formed over thermally thin filter paper in microgravity environment (initial oxygen concentration; 21 vol.%).

3.3. End view of spreading flame in a microgravity and quiescent environment

In the image obtained from the side-view camera, an interesting phenomenon was observed in the flame spread when the flow velocity was 0 cm/ s. That is shown in Fig. 3. The spreading flame is not visible in the image at 85 s. However, as shown in the image at 90 s and 95 s, a green region appeared, and then the green circle area was gradually developed around the flame as time progressed. As can be seen in the figure, the color of the green region became darker with the passage of time although the green region kept the same shape. On the other hand, the image at 120 s shows that the color at the center of the green circle region was slightly darker. Then, in the image at 130 s when the flame extinction occurred, the color of the green region became almost uniform. The green area is considered to be the fuel vapor generated by the pyrolysis of the filter paper. The fuel vapor was condensed and turned into fine fuel droplets, and the fuel droplets were visualized by the green LED light as shown in the images. In the image at 120 s, the slightly darker area in the center of the circular green region is thought to be the combustion reaction region. Therefore, in the 130-second image, the intensity of the green region becomes almost uniform over the entire region because the flame has been extinguished. It is unclear what kind of physical mechanisms causes this phenomenon. Therefore, further analysis and examination of the result are needed.

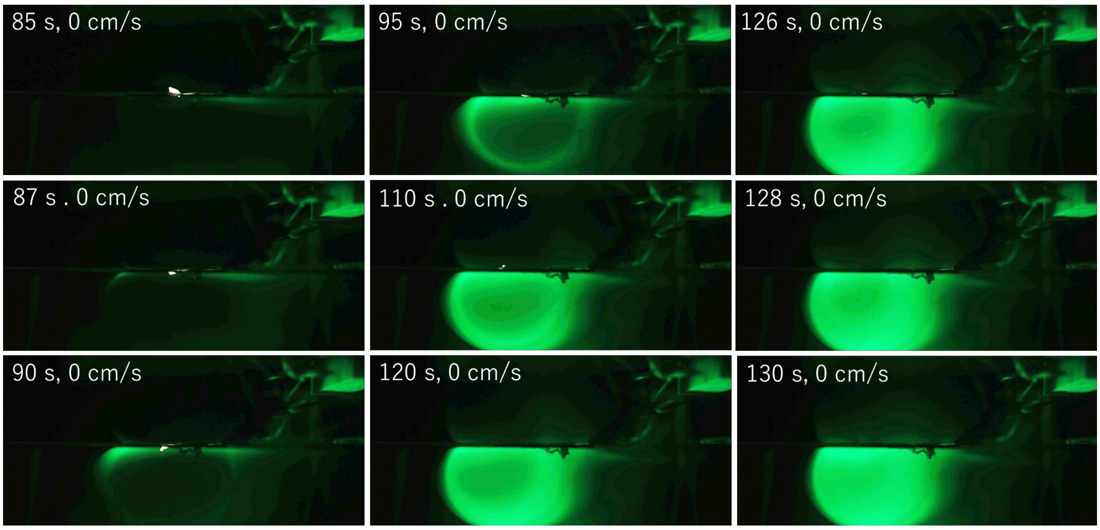


Figure 3. Side view images of opposed flow flame spreading in quiescent gas and microgravity environment

3.4. *x-t* diagram of the opposed-flow flame spread in a microgravity environment

Figure 4 shows the relationship between the traveling distance of the pyrolysis front and the time elapsed from the start of the experiment. The vertical lines in the figure indicate the timing when the flow velocity decreased from one value to another. The slope of the graph indicates the magnitude of the flame spread rate. From Fig. 4, it is seen that the plot of data shows a constant slope at each flow velocity. At 2.6 cm/s, the spread rate was 1.5 mm/s. At 2.6 cm/s, the flame spread rate shows 1.5 mm/s, 1.1 mm/s at 2.1 cm/s, and 0.9 mm/s at 1.3 cm/s. Finally, when a quiescent atmosphere environment was achieved, the flame spreading rate indicates 0.2 mm/s. Thus, it is found that at the flow velocity of 0 cm/s, the flame has very small spread rate. Judging only from this graph shown in Fig. 4, it seems that a steady flame spreading is established in each period with constant flow velocity.

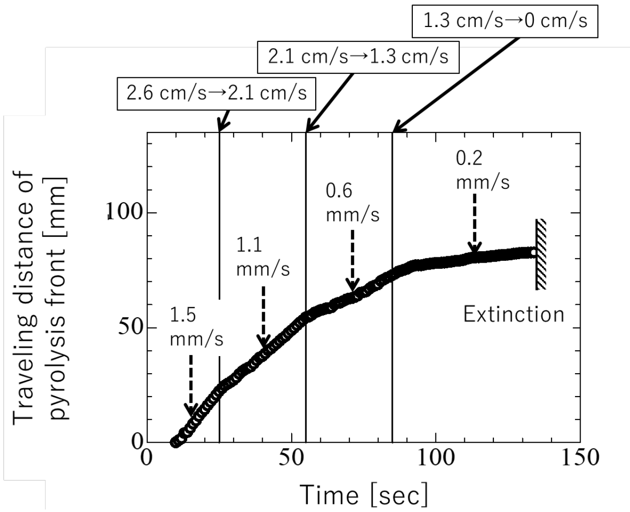


Figure 4. Relationship between elapsed time from the start of the combustion experiment and traveling distance of pyrolysis front

4. Concluding Remarks

In this report, one of the results obtained from the combustion experiments of a filter paper performed on International Space Station in the FLARE project was explained briefly. The Solid Combustion Experiment Module (SCEM) is working without problems, and high-quality solid combustion data in a microgravity environment are obtained under very low flow velocity conditions. In the experimental result, it is found that the diffusion flame formed over a thermally thin paper in an opposed flow survives by changing from a two-dimensional flame shape to a three-dimensional flame shape even at a flow velocity of 0 cm/s. Although not presented here, we have also succeeded to carry out the experiments of a concurrent-flow flame spread. In the future, we expect to clarify the diagrams of the limiting oxygen concentration for opposed and concurrent flow spreading flames.

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