JASMAC

Conference of the Japan Society of Microgravity Appllication

OS3-3

FLARE-3 プロジェクト：回転筐体を用いた低重力環境下における固体材料の火災安全評価手法の構築に向けて

FLARE-3 project: Toward the Development of a Flammability Evaluation Method of Solid Materials Under Partial Gravity Environments Employing a Centrifuge

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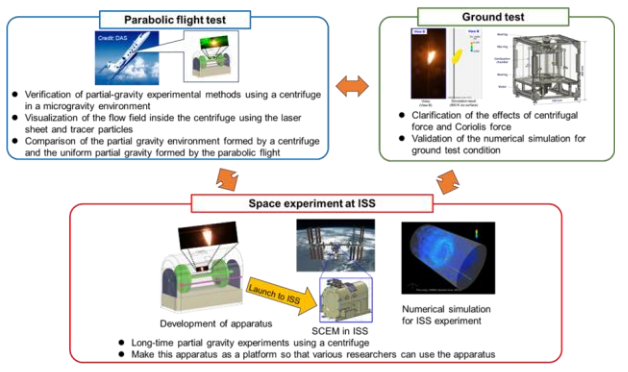
Abstract: Fire safety is one of the most critical concerns in future manned space missions, particularly under partial gravity environments such as those on the Moon and Mars. While the flammability of solid materials has been extensively studied under microgravity, their behavior in partial gravity remains unclear. The FLARE-3 project aims to establish a flammability evaluation method for solid materials under partial gravity conditions by developing an experimental apparatus equipped with a centrifuge for the International Space Station (ISS). As part of a feasibility study, parabolic flight experiments were conducted to validate the proposed methodology. These experiments confirmed that the Coriolis force significantly affects flame and flow fields in the confined chamber of a small-diameter centrifuge. Flow visualization using a laser sheet and tracer particles, along with numerical simulations, demonstrated consistent flame tilting and circulation flow patterns, showing good agreement between experiments and predictions. These findings provide fundamental insights into flame behavior under artificial partial gravity and contribute to the design of future space experiments.



Keywords: Partial gravity, Flammability of solid materials, Parabolic flight experiment

1. Introduction

Fire safety is one of the most important issues in manned space explorations. The flammability of solid materials in the microgravity environment has been studied by FLARE (Flammability Limits At Reduced-g Experiment) project[1]. In the Artemis program, on the other hand, astronauts will be sent to the Moon or even Mars in the future. Therefore, the fire safety of bases in partial gravity environments, which are different from the microgravity or Earth ground environments, should be ensured. However, the flammability of solid materials in partial gravity environments has not been clarified yet. In the FLARE-3 feasibility study[2,3], which is one of the following projects of the FLARE project, the space experiment apparatus for the International Space Station (ISS) is developed to investigate the flammability of solid materials in partial gravity conditions. In this paper, the outline of the FLARE-3 project and the recent results of parabolic flight experiments for the flame spread over solid material under the partial gravity conditions are introduced.

2. Outline of FLARE-3 project

Figure 1 shows the outline of the FLARE-3 project. The final goal of this project is the development of a platform for long-term partial gravity combustion experiments of solid materials, and the clarification of the flammability of solid materials under partial gravity conditions. To achieve this goal, the experimental apparatus with a centrifuge for ISS is now under development. Since there is a limitation on the rotational radius of the centrifuge of the apparatus due to the size of the combustion chamber of the Solid Combustion Experiment Module (SCEM), which is the module we are planning to utilize in the ISS in this project, the effect of the Coriolis force is not negligible. To examine the effect of the Coriolis force, the ground test apparatus employing a centrifuge has been developed. Using this ground test apparatus, how the combination of centrifugal force and the Coriolis force can affect the flame spread over solid materials is studied. The parabolic flight experiments were also conducted to verify the partial gravity experimental methods using a centrifuge in a microgravity condition in January 2025. Not only the validation of the basic function of this experimental method using a centrifuge, but also the flow visualization test using a laser sheet and small tracer particles and the comparison of the partial gravity environment formed by a centrifuge and the uniform partial gravity environment formed by the parabolic flight itself were conducted. Basically, the parabolic flight tests were successfully conducted, and the output for this series of parabolic flight experiments will be utilized for the development of the apparatus for future space experiments in ISS.

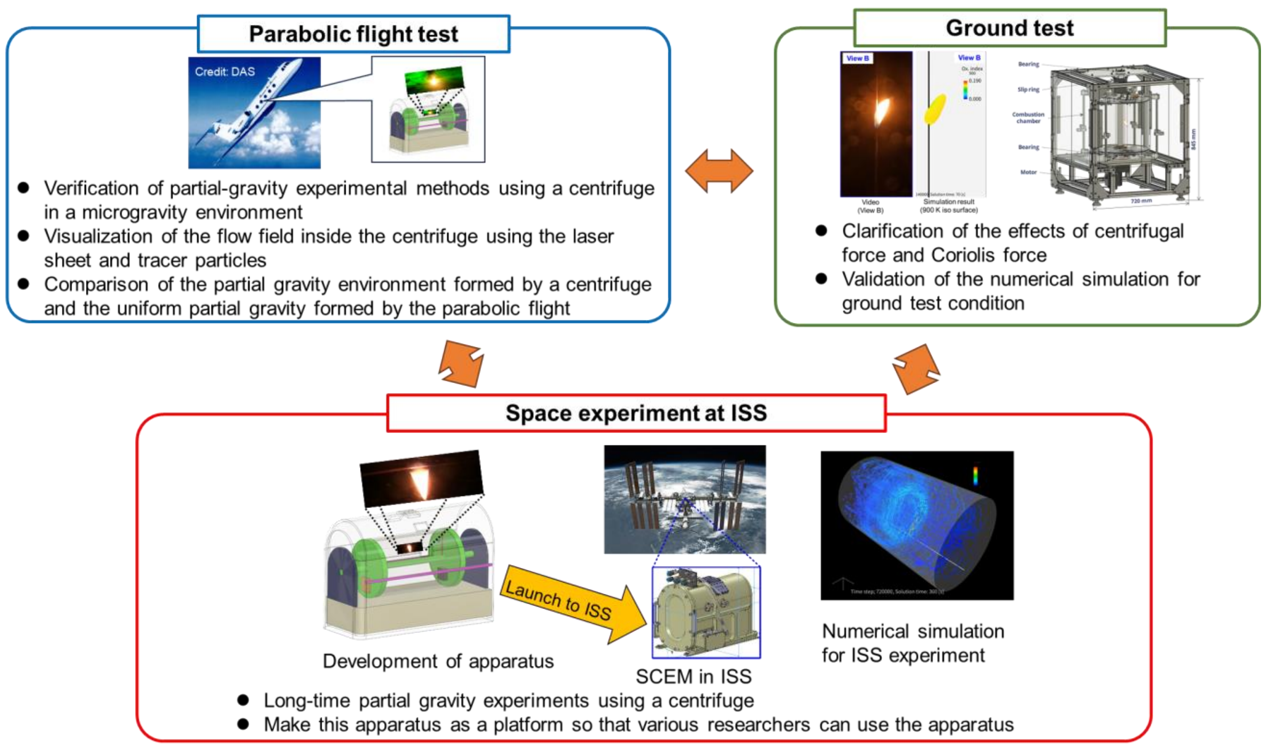


Figure 1. Outline of FLARE-3 project

3. Parabolic flight experiments

For the verification of partial gravity experimental methods using a centrifuge, a series of parabolic flights was conducted in January 2025. The parabolic flights were provided by Diamond Air Service Co. Ltd. Figure 2 shows the schematic of the centrifuge used in the parabolic flights. The inner diameter and volume of the centrifuge are 180 mm and 8.2 L, respectively. The radial position of the sample was set at 55 mm. There were three cameras to observe the flame behavior during the flame spread over the samples. The laser sheet and tracer particle dispersion system were employed for the flow visualization during the flame spread experiment.

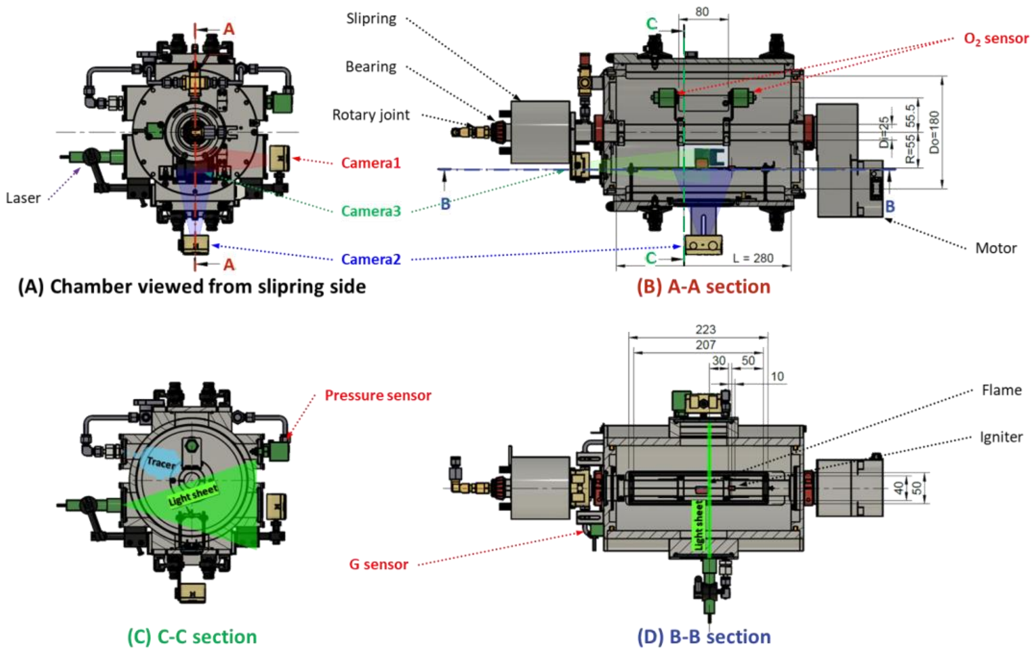
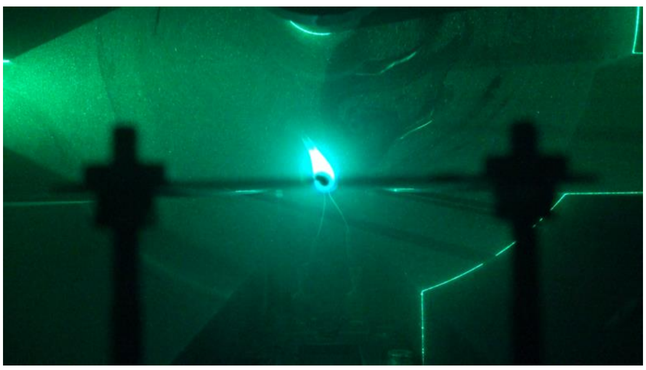
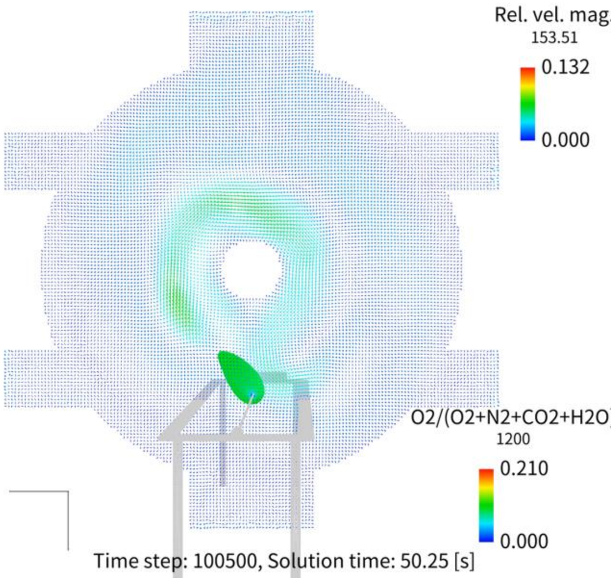


Figure 2. Schematic of the centrifuge for parabolic flight experiments



(a) Photo of the flame taken by Camera 3, and flow visualization by laser sheet and tracer particles



(b) Iso-surface of the temperature = 1200 K and velocity vector distribution at the laser sheet location calculated by the numerical simulation

Figure 3. (a) Image of the flame and flow visualization by sheet laser with tracer particles, and (b) temperature iso-surface and velocity vector distribution at the laser sheet position predicted by numerical simulation.

The outer diameter of the wire sample was 0.8 mm, with the core diameter of 0.5 mm (0.15 mm thickness of insulation). LDPE was employed as the insulation material, and two kinds of core materials, which were Cu and NiCr, were employed. The artificial partial gravity environment was formed by rotating the centrifuge during the microgravity parabolic flight. The ignition of the wire sample was made by the electrically heated wire. During the experiment, the movies of flame by the three cameras and the oxygen partial pressures at two different positions were recorded.

Figure 3 (a) shows an example of the flame image with the flow visualization by the laser sheet and tracer particles. It is observed that the flame tilts toward the direction of the centrifuge rotation (clockwise direction for the Camera 3 view). This tilt is caused by the Coriolis force, which appears significantly in the artificial gravity field formed by a small-diameter centrifuge. Due to the effect of the Coriolis force, there is an entire flow of circulation in the clockwise direction in the chamber. Figure 3 (b) shows the iso-surface of the gas temperature (= 1200 K) and velocity vector distribution at the laser sheet location obtained by the numerical simulation. The same method as the previous study by N. Hashimoto et al.[2)] was employed for the numerical simulation in this study. The inclination of the flame was well reproduced by the simulation, and the clockwise circulation flow was also well predicted.

4. Conclusions

In the FLARE-3 project, the space experiment apparatus for the International Space Station (ISS) is being developed to investigate the flammability of solid materials in partial gravity conditions. The experimental apparatus for the space experiment, which employs the centrifuge to form artificial partial gravity in the combustion chamber, is now under development. For the verification of partial gravity experimental methods using a centrifuge, a series of parabolic flights was conducted. It was observed that the flame and flow field inside the centrifuge were affected by the Coriolis force. The behaviors of the flame and flow field inside the centrifuge were well predicted by the numerical simulation. Further analysis of the data taken by the parabolic flight experiments will be made in the future.

Acknowledgments

This work was supported by JAXA "Kibo" utilization feasibility study, and JSPS KAKENHI Grant number JP23K13258 and JP24K21649.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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