JASMAC
Conference of the Japan Society of Microgravity Appllication

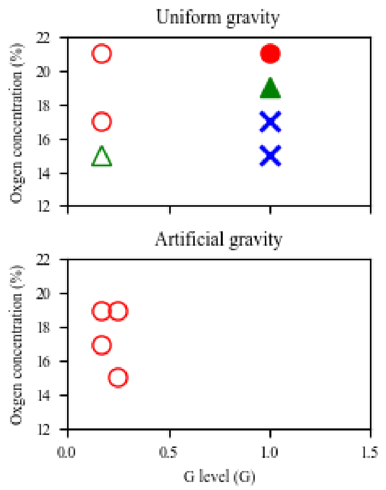
PS06

パラボリックフライトと遠心機により形成した人工低重力場と一様重力場における電線水平燃え広がり特性の比較

Comparison of Horizontal Flame Spread Characteristics of Electrical Wires in Artificial Low-Gravity and Uniform Gravity Fields Created by Parabolic Flight and Centrifuge

平賀健真 [1*], 金山颯吾 [1], 金野佑亮 [1], 橋本望 [1], 藤田修 [1],
Kenshin HIRAGA[1], Fugo KANAYAMA[1], Yusuke KONNO[1], Nozomu HASHIMOTO[1], Osamu FUJITA[1]
[1] 北海道大学, Hokkaido University,
* **hiraga.kenshin.m7@elms.hokudai.ac.jp**

Limiting oxygen concentration



Abstract: To assess fire risks on the Moon or Mars accurately, an understanding of the flammability of solid materials under relevant gravity and atmospheric conditions is essential. This study compares horizontal flame spread over electrical wires in two low-gravity conditions: a uniform gravity field formed by parabolic flight and an artificial gravity field generated by a centrifuge. Experiments using Cu core wires coated with LDPE were conducted under gravity levels of 0.166–0.249 G and oxygen concentrations of 15–21%. In the artificial gravity field, flames tilted due to centrifugal and Coriolis forces and appeared brighter than in uniform gravity at the same G-level. Low gravity reduced the limiting oxygen concentration, promoting combustion. Notably, flame spread occurred at 15% oxygen in 0.249 G artificial gravity, whereas extinction occurred in 0.166 G uniform gravity. This enhancement of flammability is attributed to recirculating hot gases in the centrifuge, which preheat the sample and accelerate pyrolysis. However, excessive promotion under artificial gravity suggests that its direct use for long-duration, reproducible combustion testing requires further study. Evaluation methods that account for recirculating flow effects should be developed to ensure accurate fire risk assessment in such environments.

Keywords: **Low-gravity combustion, Horizontal flame spread, Artificial gravity, Electrical wire, Limiting oxygen concentration**

1. Introduction

Fire safety is one of the most critical considerations in manned space habitats and planetary exploration missions. In low-gravity environments, such as those on the Moon or Mars, flame spread behavior and combustion characteristics can differ significantly from those on Earth. Accurate assessment of fire risks in these environments requires experimental data obtained under relevant gravity and atmospheric conditions.

Artificial gravity generated by a centrifuge provides a means to achieve stable and adjustable gravity levels on the ground or in space, potentially enabling longer-duration combustion experiments. However, the flow field in artificial gravity, influenced by centrifugal and Coriolis forces, may alter flame behavior in ways not observed under uniform gravity.

This study investigates horizontal flame spread over electrical wires under two low-gravity conditions: a uniform gravity field simulated by parabolic flight and an artificial gravity field created by rotating a combustion chamber during flight. By comparing flame appearance and limiting oxygen concentration between these environments, the effects of centrifugal and Coriolis forces on combustion behavior are evaluated, and the potential and challenges of using artificial gravity for low-gravity combustion studies are discussed.

2. Experimental Method

2. 1 Experimental Apparatus

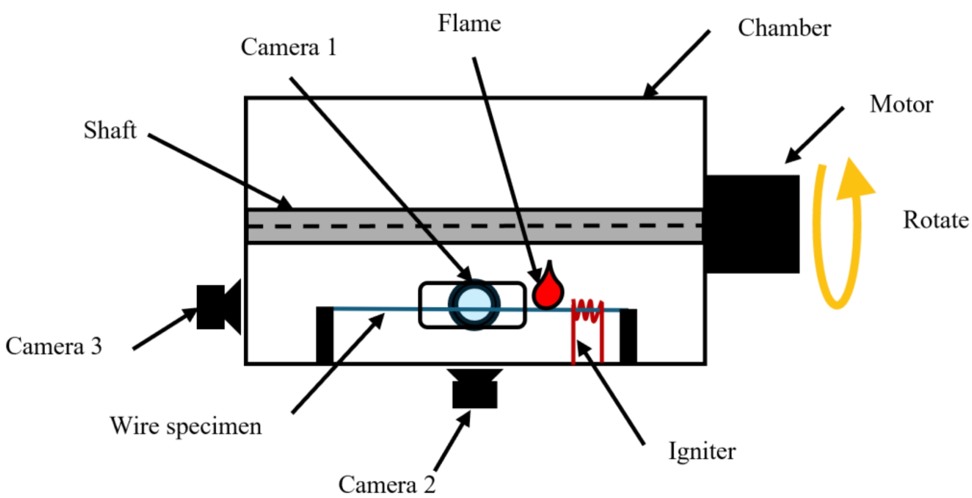


Figure 1. Schematic of the chamber

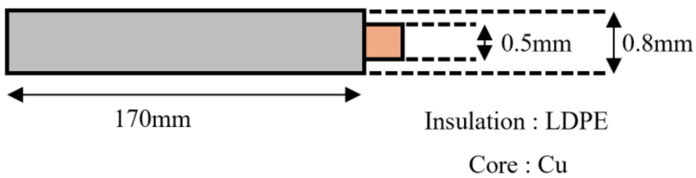


Figure 2. Wire specimen

Figure 1 illustrates a schematic of the centrifuge. The main components include a motor, three visual cameras, and a combustion chamber. The wire specimen used was a Cu core wire coated with LDPE (Figure 2), and ignition was achieved using a heated coil.

2. 2 Experimental Conditions

In this study, experiments were conducted under two gravity conditions: a uniform gravity field simulated by parabolic flight and an artificial gravity field created by rotating the combustion chamber during the flight. Both the microgravity and low-gravity phases provided by the parabolic flight lasted approximately 20 seconds, and the microgravity level achieved was approximately 3×10^{-2} G (1G = 9.8 m/s²). The parabolic flights were operated by Diamond Air Service Co., Ltd., using an MU300 aircraft.

The pressure inside the combustion chamber was fixed at 100 kPa. The internal gas was prepared by mixing nitrogen and oxygen, and the oxygen concentration was varied in the range of 15–21%.

Experiments were conducted under four centrifugal force conditions: 0.166 G, 0.249 G.

3. Experimental Results and Discussion

3.1 Flame appearance

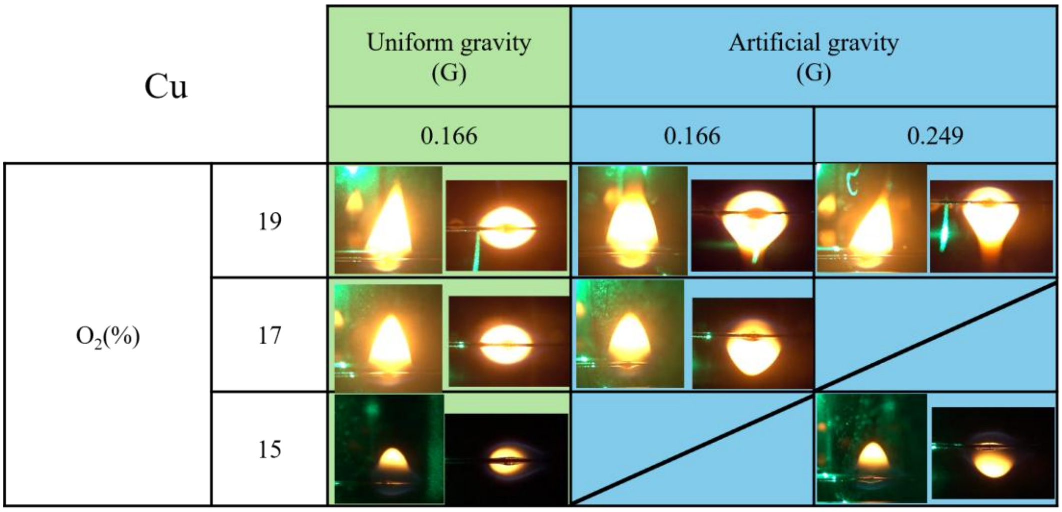


Figure 3. Flame images under each condition. For each condition, the left image was captured by Camera 1, and the right image by Camera 2.

Figure 3 presents a series of flame-spread images of Cu core samples, captured by Camera 1 (left images) and Camera 2 (right images). Comparing the flame shapes between the uniform gravity field and the artificial gravity field, a clear difference can be seen in the images taken by Camera 2. In the uniform gravity field, the flame rises vertically upward, and in the Camera 2 view, a vertically symmetrical flame shape relative to the sample is observed. In contrast, in the artificial gravity field, the Camera 2 images show an asymmetrical flame shape, with the downstream end of the luminous flame located below the sample. This is caused by the flame, while rising radially under the influence of centrifugal force, being deflected in the circumferential direction due to the Coriolis force.

For flame spread over Cu core samples, at oxygen concentrations of 19% and 17%, no notable differences in flame shape were observed between gravity magnitudes or types, nor between the 19% and 17% conditions themselves. However, under the 15% condition, the flames were noticeably dimmer. Under the uniform gravity field at 0.166 G with an oxygen concentration of 15%, the flame was extinguished partway through burning, suggesting that the limiting oxygen concentration for the uniform gravity field at 0.166 G is close to 15%.

In the ground-based uniform gravity condition, no flame spread was observed at an initial oxygen concentration of 15%. However, flame spread was confirmed under the uniform gravity field at 0.166 G and the artificial gravity field at 0.249 G. These results indicate that, regardless of whether the gravity field is uniform or artificial, low-gravity environments promote combustion.

3.2 Limiting Oxygen Concentration

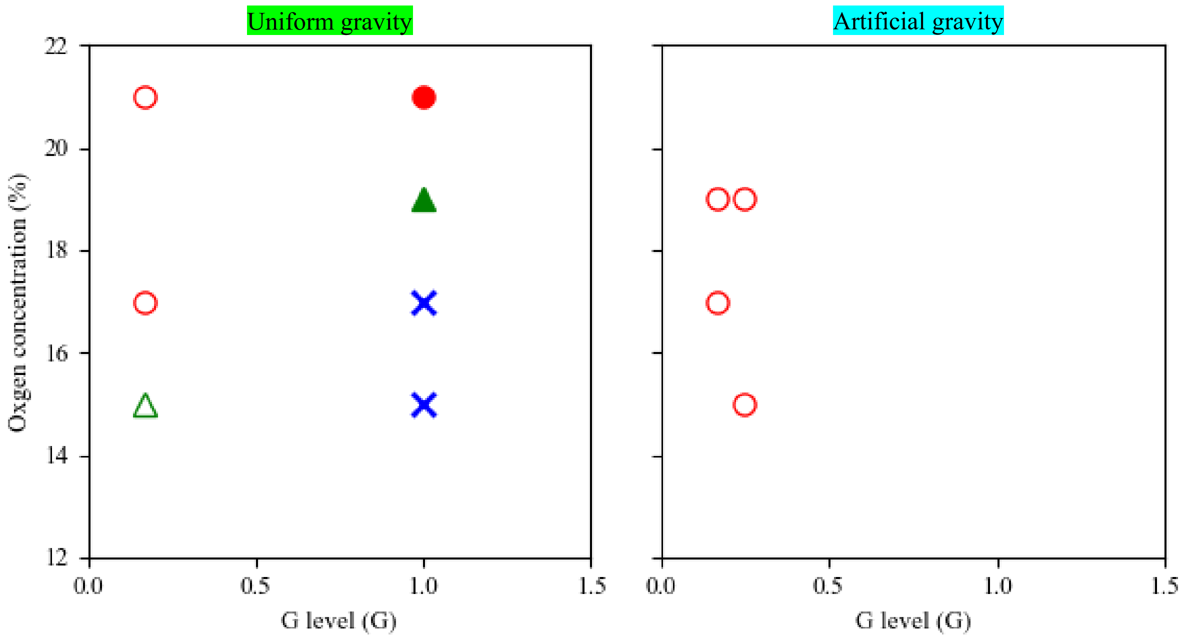


Figure 4. Relationship between limiting oxygen concentration and gravity for copper samples. The graph on the left represents the uniform gravity condition, while the graph on the right represents the artificial gravity condition. ● (filled) indicates ignition on the ground with complete consumption of the sample, and ▲ (filled) indicates ignition on the ground followed by extinction during burning. ○ (hollow) indicates ignition during the aircraft experiment with sustained burning throughout the low-gravity period, △ (hollow) indicates ignition during the aircraft experiment followed by extinction before the end of the low-gravity period. × indicates no ignition.

Figure 4 shows the relationship between limiting oxygen concentration and gravity level for Cu core wire specimen. In the aircraft experiment, ignition was confirmed under all conditions.

First, regarding the uniform gravity condition, the limiting oxygen concentration was found to be 18–19%, and no ignition occurred at 17% at 1 G condition. However, under the 0.166 G condition, flame spread was observed at an oxygen concentration of 17%, and ignition was confirmed even at 15%. This indicates that low gravity provides an environment that promotes combustion.

Next, regarding the artificial gravity condition, flame spread occurred under all conditions in the aircraft experiment. Furthermore, under the artificial gravity condition of 0.249 G, flame spread occurred at 15% oxygen concentration. In contrast, under the uniform gravity condition of 0.166 G, combustion was extinguished before completion at 15% oxygen concentration. This suggests that an artificial gravity environment promotes combustion more effectively than a uniform gravity environment.

One possible reason for this enhancement in combustion under artificial gravity is the influence of the circulation flow formed inside the centrifuge.

In a uniform gravity field, combustion gases collide with the rotating shaft inside the combustion chamber (Fig. 5) and lose heat. In contrast, in an artificial gravity field, the combustion gases avoid the shaft and return to the sample location while retaining their thermal energy. This flow of combustion gases can preheat the sample, reducing the temperature difference between the sample and the surrounding gases, which may make it less susceptible to extinction by convection. Additionally, preheating of the sample can accelerate the pyrolysis rate, which may further contribute to the promotion of combustion.

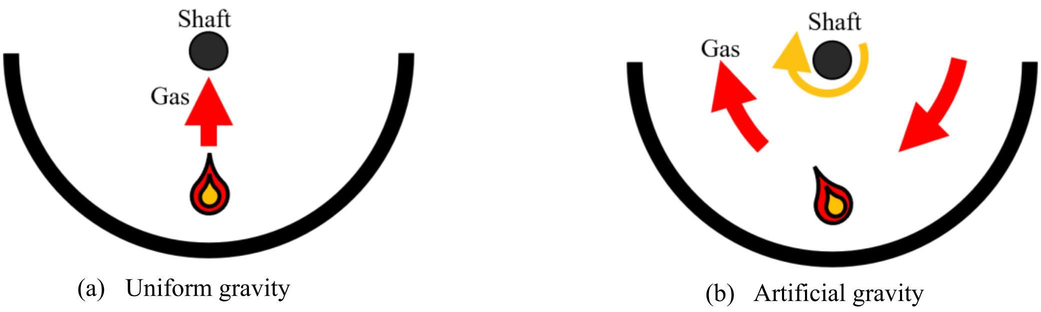


Figure 5. Direction of combustion gas flow inside the ~~chambe~~chamber

4. Conclusion

This study compared horizontal flame spread over electrical wires in two low-gravity environments: a uniform gravity field formed by parabolic flight and an artificial gravity field generated by a centrifuge. In the artificial gravity field, flames were tilted due to centrifugal and Coriolis forces and appeared brighter than in uniform gravity at the same G-level. Low-gravity environments reduced the limiting oxygen concentration, indicating enhanced flammability. Notably, flame spread occurred at 15% oxygen in 0.249 G artificial gravity, whereas extinction occurred in 0.166 G uniform gravity. This enhanced flammability is attributed to the recirculation of hot combustion gases in the centrifuge, which preheated the sample and accelerated pyrolysis. However, the promotion of combustion in artificial gravity can be excessive, suggesting that direct application of this environment for long-duration and reproducible combustion testing requires further study. Future work should focus on developing evaluation methods that account for the effects of recirculating flows to ensure accurate assessment of fire risks under artificial gravity conditions.

5. Acknowledgments

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

6. References

(1) Y. Konno, S. Ishikawa, N. Hashimoto, O. Fujita, "Evaluation of Buoyant Flow Velocity Induced by Centrifugal and Coriolis Acceleration During Downward Flame Spread Over Thin Wire in a Centrifuge", in: 52nd Int. Conf. Environ. Syst., Calgary Canada, 2023

(2) Y. Konno, S. Ishikawa, N. Hashimoto, O. Fujita: "Downward flame spread and extinction over electric wires placed in a ground-based centrifuge," *Proceedings of the Combustion Institute*, Vol. 40 (2024), in press.

(3) S. Takahashi, H. Ito, Y. Nakamura, O. Fujita, "Extinction limits of spreading flames over wires in microgravity," *Fire Safety Journal*, Vol. 58, 2013, pp. 170–177.

(4) Dietrich, D.L., "Flame Spread Over Thin Fuels in Actual and Simulated Spacecraft Atmospheres", NASA/TM-2001-210807, 2001.