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Experimental study on flame spread over a PMMA flat sheet on the Ground centrifuge

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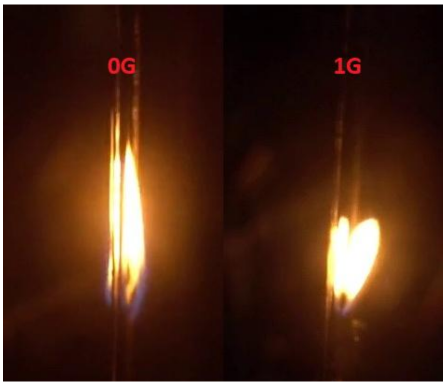

Abstract: This study investigates the flame behavior under centrifugal force using a ground-based centrifuge. The poly-methyl methacrylate (PMMA) is used as a sample for this study. Rotational speed of the centrifuge was varied to create centrifugal force equivalent to 0 G to 1 G at the sample location. Flame behaviour is recorded using two cameras. The effects of artificial gravity and varying oxygen concentrations, obtained from an oxygen sensor, on flame shape and flame spread rate (FSR) were examined. The results show that increased centrifugal force induces a buoyancy force, tilting the flame toward the rotational axis and reducing the FSR. Flame spread rate with respect to oxygen concentration obtained. The findings of this study will be utilized for the development of the future centrifuge apparatus for ISS experiment..

Keywords: **PMMA, Centrifuge, Microgravity, Flame spread**

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 researched by FLARE (Flammability Limits At Reduced-g Experiment). However, the fire safety of solid material in low partial gravity environment such as on the Moon or Mars environment is also important in the future. However, the flammability of solid materials in partial gravity environments has not been clarified yet. In FLARE-3 feasibility study, which is one of the following project of FLARE project, the flammability of solid materials in partial gravity environments is studied. In FLARE-3 project, the development of centrifuge in the International Space Station (ISS) is planned for building up the platform for the long-term partial gravity fire safety experiment. For the development of the above-mentioned centrifuge for the space experiment, the understanding of the effect of the flow field inside the centrifuge on the flame spreading over solid material is important[1)].

Flammability limit of thin poly-methyl methacrylate (PMMA) sheets and polycarbonate (PC) with varying thicknesses for the micro gravity condition were studied using parabolic flights[2)]. However, the study examining the flame spread over flat sheet sample in a centrifuge is significantly limited. In this study, the flame spread in the PMMA sample in the ground-based centrifuge was investigated.

2. Experimental

Figure 1 shows the custom-designed ground-based centrifuge used in this study. The system consists of an aluminum frame, a motor (BXM6200M-10FR, Oriental Motor Co., Ltd.), a slip ring (SRC100-16p, Kyoei Denki Co., Ltd.), and a sealed combustion chamber. The chamber has an inner diameter of 390 mm, a vertical height of 340 mm, and an internal volume of approximately 39 liters. The rotational shaft has an outer diameter of 70 mm[1)].

The combustion chamber is hermetically sealed, which allows experiments to be conducted under specific gas compositions and even low-pressure conditions. As shown in Fig. 2, the PMMA sample of 160 mm length, 20 mm width & 0.2 mm thickness was placed parallel to the rotational axis, ensuring that the centrifugal force acts consistently along the flame's direction of spread. The distance from the rotational axis to the specimen is 120 mm. This PMMA sample is sandwiched in a holder using clips. In this study, all experiments were conducted with a counterclockwise rotation.

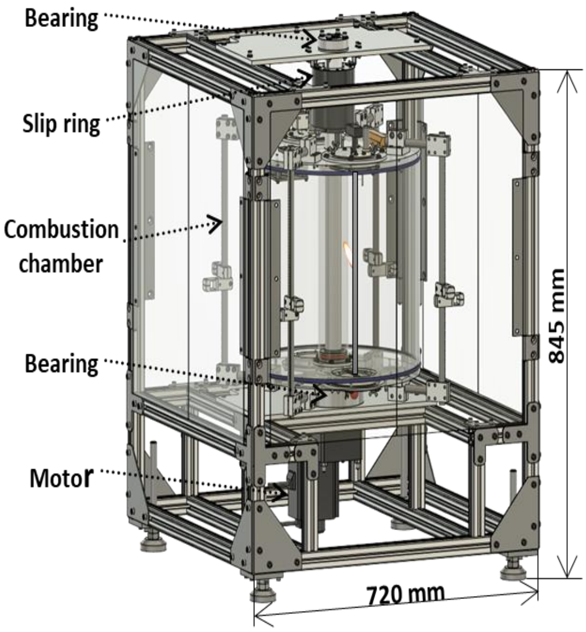

Fig. 1. Overall view

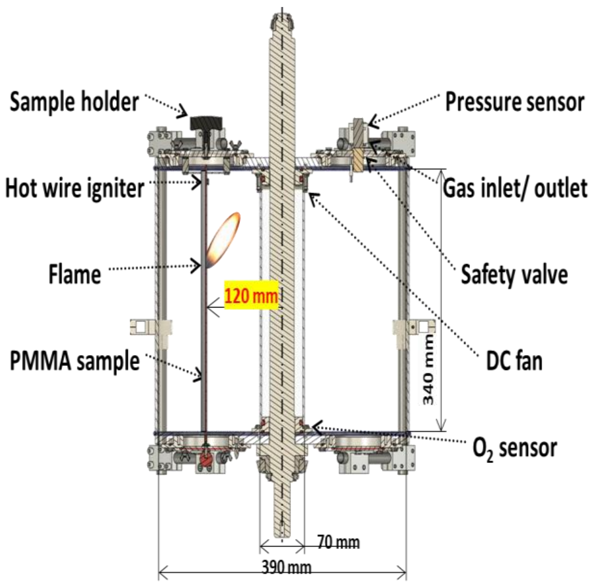

Fig. 2. Combustion chamber

The system includes multiple sensors and recording equipment: A pressure sensor (PPX-R01NH-6M-KA, CKD Co., Ltd.), An oxygen partial pressure sensor (JKO-25L3, JIKCO Co., Ltd.), and two GoPro HERO10 Black cameras. All time-dependent data—pressure, oxygen concentration, and motor speed—were logged using a data logger (midi LOGGER GL240, Graphtec Co., Ltd.) via the slip ring.

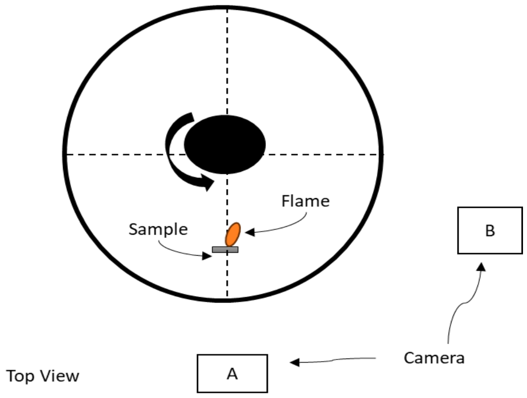

Fig. 3. Position of Two Cameras

Figure 3 shows the placement of two cameras, Camera A & Camera B. Camera A is focused towards the rotational axis from outside and captures a front view, whereas Camera B captures a side view. The sample was ignited at the upper part by an electrically heated coil using a DC power source. The power supply to the igniter was 90 watts for 10 seconds. Once the sample ignited flame spreads downward, which has been observed by the cameras. During the rotation process of sample ignitions start after the Gas inside the chamber reaches the rotational speed (Rigid body rotation).

In this study Rotational speed of the centrifuge is varied from 0 G to 1 G. The total pressure inside the chamber is kept at 100 kPa. The starting oxygen pressure varies from 18 percent to 21 percent using the combination of N2 and O2.

3. Results & Discussion

3.1 Flame shapes

Figure 4 shows the instantaneous flame shapes at different centrifugal forces of both cameras (A and B) at an oxygen concentration of 19%. In the absence of centrifugal force (Gcent = 0 G), the flame is symmetric about its axis. As we increase the rotational speed, centrifugal force applies to the flame, and the downstream is tilted away from its axis. Buoyancy force is induced due to centrifugal force, and the flame is tilted towards the center of the rotational axis.

Therefore, the more centrifugal force is applied more the flame tilts towards the rotational axis. However, at higher centrifugal forces, the asymmetric flame is observed from camera 'A' which may be due to the flow of the gases inside the chamber, which is more dominant at higher rotational speed.

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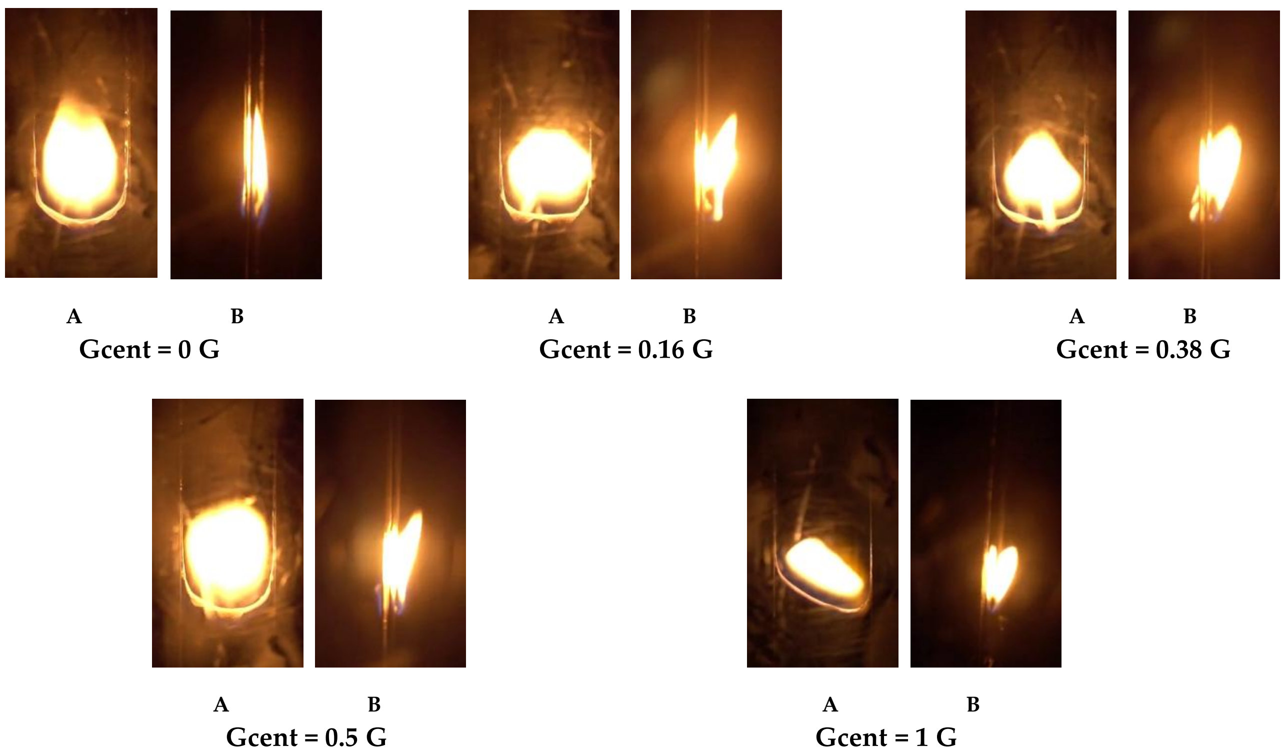
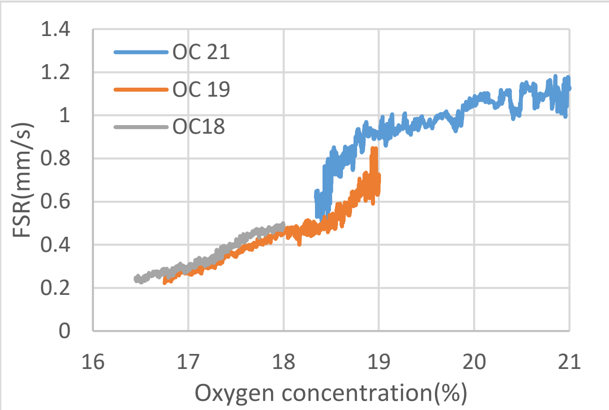


Fig.4. Photographs of the flame at oxygen concentration 19% under different centrifugal forces

3.2 Flame spread rate (FSR)

The total pressure inside the chamber and the oxygen partial pressure are measured using a sensor mounted in the experimental setup. The upstream and downstream points of the captured flame image are tracked by an in-house-designed Python code. The speed of flame varies with respect to the oxygen concentration available inside the chamber. The instantaneous Flame spread rate is calculated by applying a Savitzky-Golay filter to the flame motion history. The instantaneous flame spread rate is synchronized with the oxygen concentration available at that moment and is plotted in Figure 5.



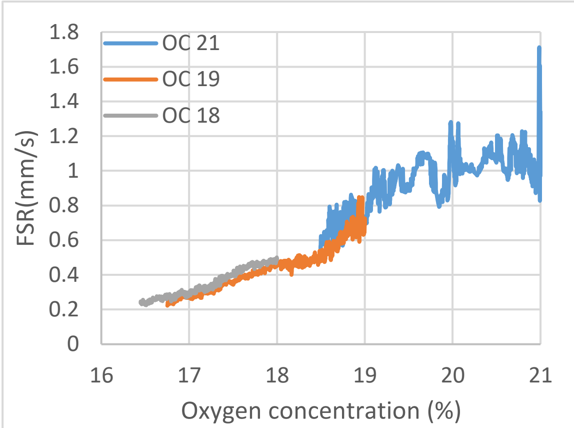
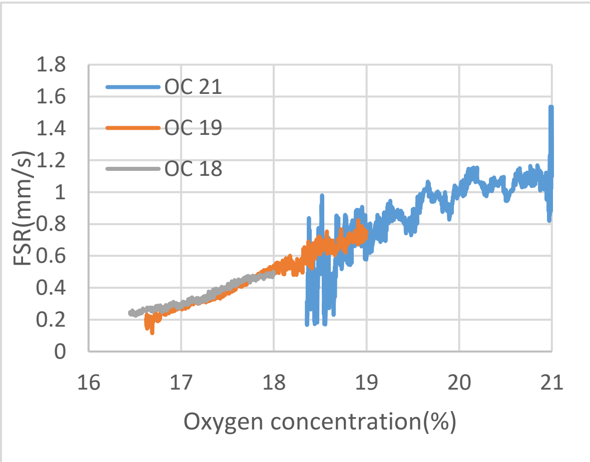


Fig.5(a) Centrifugal force = 0 G

Fig. 5(b) Centrifugal force = 0.16 G



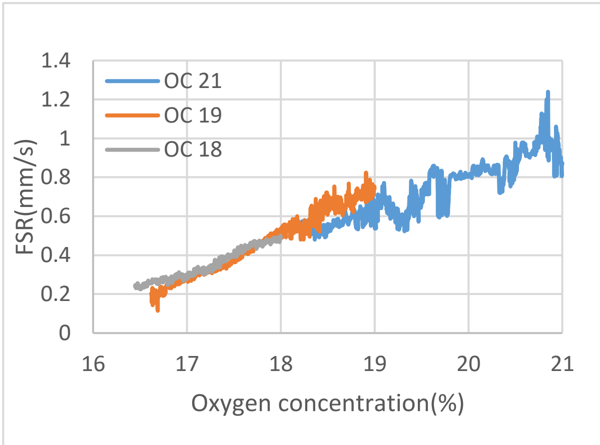


Fig.5(c). Centrifugal force = 0.5 G

Fig. 5(d). Centrifugal force = 1 G

Fig.5. Plot of Instantaneous Flame spread rate (FSR) vs oxygen concentration with initial oxygen concentration (OC) starting from 21%, 19% and 18% under different centrifugal forces

. Fig.5. shows the plot of the instantaneous flame spread rate with respect to the oxygen concentration inside the chamber with an initial oxygen concentration of 21%, 19% and 18% under different centrifugal forces. In all experiments with an initial oxygen concentration of 21%, the samples were fully burned. However, flames often extinguish before completely burning the sample, especially under higher centrifugal forces at lower initial oxygen concentrations. At a lower initial oxygen concentration, a more stable flame is observed. As the centrifugal force acting on the flame increased lower the flame spread rate was observed. At higher centrifugal force, the tendency of the flame to tilt away from its axis increases with results in less amount of heat left to carry the combustion of the PMMA sample. Therefore, the Flame spread rate decreases with increasing speed of rotation.

The overall trend indicates that both higher centrifugal force and lower oxygen concentration reduce the FSR. This is due to a combination of increased flame tilt and heat loss, which together hinder the flame's ability to propagate in the PMMA sheet

4. Conclusion

This study examines the effect of artificial gravity, generated by a ground-based centrifuge, on the flame spread behavior of a PMMA flat sheet sample. The results demonstrate that increasing centrifugal force introduces a buoyancy force on the flame, causing the flame to tilt toward the center of rotation. This tilt increases with increasing rotational speed. Tilting of the flame leads to heat loss and ultimately reduces the flame spread rate. Additionally, at lower oxygen concentrations flame appears to be more stable but limits the flame propagation speed. These combined effects highlight the sensitivity of flame dynamics to both gravity and oxygen environment. The findings of this study will be utilized for the development of the future centrifuge apparatus for ISS experiment.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used GPT-4o, DeepL AI to enhance the English language usage. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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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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