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滑斜面を用いた低重力場発生装置の開発と検証

Development of partial-gravity generator launching over a less-friction slope

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1. Introduction

To date, exploration of Lunar and Mars have been paid special attention in the space missions. With this respect, a safety management under partial gravity environment become inevitable issue. A fire is one of significant potential hazards in the space missions, thus, precise understandings on burning mechanism under partial (low)-gravity conditions ($0g$<$g_{L,\ Low}$<$1g$) must be made with our best knowledge. As is well-known feature of combustion in microgravtity[1)], candle flames (diffusion flame) tend to be spherical due to the absence of buoyancy-induced flow, suggesting that there should be significant difference on material burning character because the heat feedback from the flame to the burning specimen is strongly connected. Indeed, Sacksteder et al.[2)] showed that flammable range of thin combustible was enlarged in microgravity due to the modification of heat transfer process depending on the adopted gravity. Nakamura et al.[3)] numerically predicted that spontaneous ignition of externally heated solid fuels under various partial gravity conditions, revealing that there is "optimum" ignition condition at certain partial gravity field. Most recent ISS scientific project, code name is "FLARE"[4)], it has been experimentally revealed that the flammable feature was most pronounced at low-speed incoming flow (not microgravity), as a model of partial gravity field, which is same trend found in the prediction by Nakamura et al.[3)]. Although there are experimental data at partial gravity conditions, it is still not enough to receive sufficient data for comparisons and discussions. For this purpose, easy-access device to generate the various partial gravity conditions is highly demanded.

Researchers have made efforts to obtain such "abnormal" gravity field by developing/proposing special methodologies. For instance, controlled parabolic flight[5)], counter-weight free-fall method[6)], control the acceleration of dropping the test chamber[7)], using centrifuge facility together with zero-gravity hardware[8)]. Nevertheless, having wide range of controllable device with relatively easy-to-access (e.g., Lab-friendly design) feature is not available at present except a few proposals, namely, yo-yo mechanism proposed by Akiba et al.[9)] and Slope-sliding Method (SSMe) proposed by Nakamura and Sekimoto[10)]. Combining with centrifuge facility and microgravity facilities (drop tower, parabolic flight etc) have been recently paid attention by several groups[ex.11-12], however, the combination itself is not easy and handy (far from lab-scale tests). In the present work, we propose the extended (revised) version of SSMe which one of coauthor has been developed.

A "revised slope-sliding method" proposed in this study is followed by the concept of original SSMe yet the protocol is opposite. In the original SSMe, test chamber was set at the top of slope and the partial gravity field is achieved during the "sliding down" operation. In the present (revised) version, the test device shall be set at the bottom and it is *launched* upwardly along the slope, similarly, partial gravity field is achieved during the "climbing up" operation. Theoretically, both operations shall give the same result, however, we employed the reverse operation to receive high-quality of partial gravity level.

2. Experimental design

2.1 What is SSMe?

The principle of SSMe is briefly explained as follows: SSMe involves sliding an experimental rack down/up an inclined base. Assuming no friction between the contacting surfaces (downface of the rack and surface of the slope), during the sliding operation, only vertical component of the gravity against the slope will act on the sliding rack. With varying the slope angle, ideally, various levels of partial gravity condition shall be achieved. **Figure 1** shows the original conceptual diagram, referred from Ref. 10 (left) and the revised SSMe (right: currently work). Basic design is exactly the same, however, the protocol to obtain the partial gravity environment is different, namely, one is sliding down and the other is climbing up as described previously.

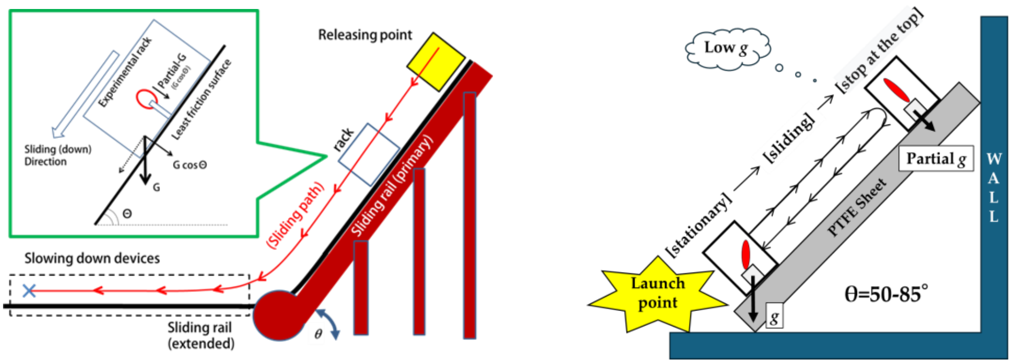

Figure 1. Overview of original SSMe[10] (left) and revised SSMe (right)

2.2 Experimental setup

Figure 2 shows a schematic diagram of the presently designed experimental setup. A PTFE sheet (1800 mm x 300 mm) coated flat wooden board was used as the low-friction surface, which is the slope in this study. Experiments were conducted at five prescribed angles; such as 50°, 60°, 70°, 80°, and 85°. The rack was released to upward at the launching point. Sprite ramp, whose wick is 7 mm of diameter and 3 mm long, was set in the rack to generate the reference flame to be studied. Considering the limited low-gravity duration (approximately 0.7-0.8 seconds), a steady diffusion flame, which is highly responsive to gravity changes, was successfully formed. Flame dynamic behavior was monitored by handy camera (GoPro Hero 10: ISO 200, shutter speed at 1/480 sec) with high-speed mode at 120 FPS. Camera was set 95 mm distance away from the center plane along the wick axis in order to capture full image of the flame. For better visibility, a blackend aluminum sheet was placed at the backside to ensure flame visibility. The fuel for the spirit lamp was a common fuel alcohol consisting of 85% methanol and 15% isopropyl alcohol. **Figure 3** shows direct photographs of experimental setup. To measure the precise gravitational values acting on the rack, an SRIC G-men GR01 *g*-sensor (resolution 0.02 *g*, response frequency is 100 Hz) was mounted on the rack.

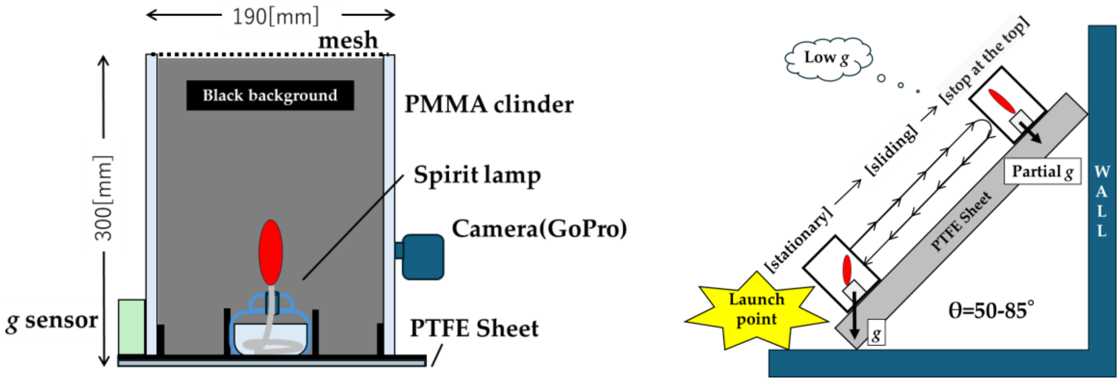

Figure 2. A Schematic diagram of the experimental setup

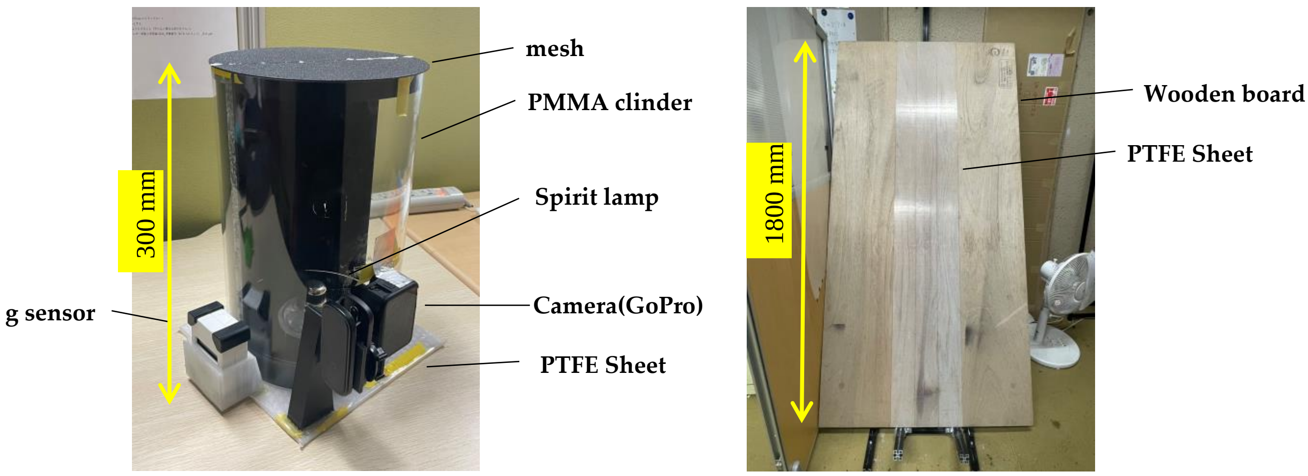

Figure 3. Photographs of experimental setup

3. Results and Discussion

3.1 Confirmation how to work this method

Figure 4 shows the output values of the *g*-sensor for each angle. At $t = 0$ sec is correspond to the time of the launch and certain acceleration is experienced for a while (~ 50 msec). Irrespective of imposed slope angles studied in this study, it only took less than 100 ms to achieve target partial gravity conditions, although the value is fluctuated around its averaged. **Table 1** summarizes the g measurements for each angle (duration of low-g period, average g, variance of g, theoretical g value ($\cos\theta$)). "Average g" and "Variance g" represent the average and variance during the partial gravity period. This summary clearly revealed that the gravitational value decreases proportionally with the angle and our simple device can offer the relatively-reasonable "expected" partial gravity condition. Difference between the theoretical (target) and obtained values are around 0.04-0.05 g, which will be caused by the friction over the slope. Furthermore, although not shown in this figure, we have recognized that the most of the jitter came from the variation in slope-direction component, implying that the treatment of surface might be effective to obtain high-quality of partial gravity environment in this method. By the way, this variation is within g-quality achieved in parabolic flight experiment which naturally generate the g-jitter during the flight operation. Although we must admit this level of difference since "no" friction surface is not available, we currently work on finding the best surface treatment. Yet, the value of variance is small enough against to the average, indicating that a sufficient partial gravity environment can be provided. Important to emphasize is that the present methodology is less-cost yet effective; this feature is nothing comparable to the other partial-g test facility available thus far.

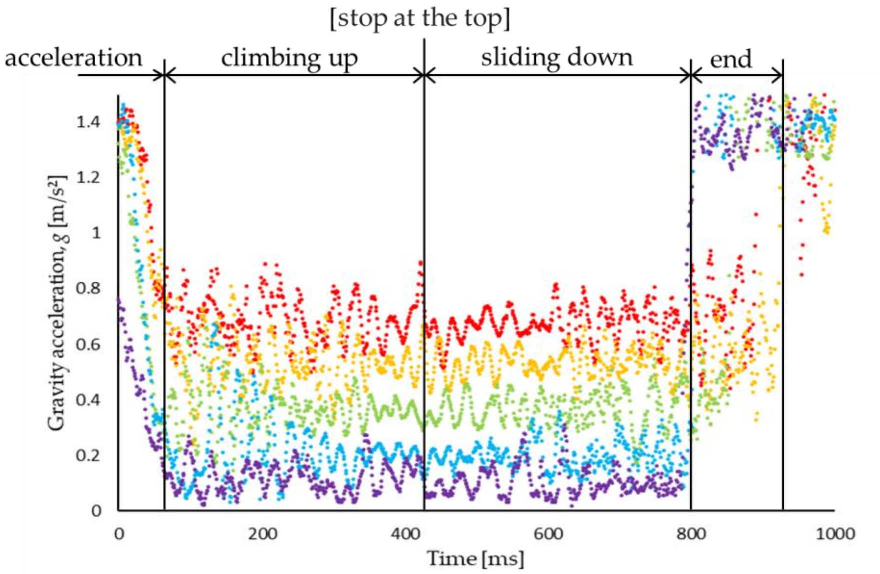

Figure 4. Time variation of output values from the g-sensor during the sliding operation

Table 1. Summary of measured g-level by g-sensor for adopted slope angle, θ.

θ	50.0°	60.0°	70.0°	80.0°	85.0°
Available time of partial-g [ms]	833	870	801	750	736
Average g [normalized by earth gravity]	0.69	0.54	0.37	0.21	0.11
Variance g	0.0068	0.0083	0.0054	0.0082	0.0028
cosθ(ideal)	0.641	0.500	0.342	0.174	0.087

3.2 Flame images under partial gravity environment

Figure 5 shows the flame images at different partial gravity conditions. Note that all figures are taken by camera which is fixed at the sliding chamber, therefore, the vertical direction of the given images are normal to the sliding surface (perpendicular to the slope). Although still figures are shown here, we confirmed that there is no apparent different during the sliding operation within the present test time (~ 0.7 s). Therefore, we listed the images taken at the end of climbing operation (namely, the rack is located at the maximum height along the slope). For better comparison purpose, the brightness was increased by 80 % to improve flame visibility. A flame image under normal gravity (1 *g*) taken under the same conditions is also included (leftmost) for comparison purpose.

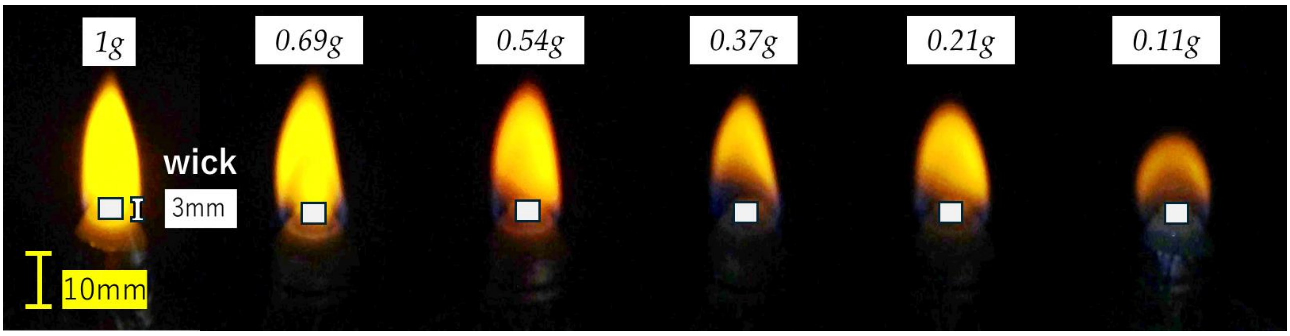

Figure 5. Appearance of flames formed over different *g*-level obtained by revised-SSMe (note that brightness was increased by 80% for better visibility)

It is clearly observed that, as the gravitational value decreases, the flame height decreases, approaching the spherical shape. Additionally, the brightness and the orange soot region decrease. This gravity response on soot generation seems opposite to what has been considered in the past works[13)], where the soot accumulation is pronounced without the presence of gravity to accelerate the fuel pyrolysis. However most of tests have used hydrocarbon fuels, which does not contain oxygen atom in the fuel. Here we used methanol so that soot generation is not pronounced as expected. According to NASA's report[13)], propanol flame under microgravity shall exhibit less-soot flame during the propagation over the liquid pool. This fact may support what we have observed here. Of course we can adopt hydrocarbon fuel using the present methodology which may exhibit the excess soot production as the gravity level reduced. Although this would be our future work, it is quite sure that the developing the lab-scale partial gravity generator can bring merits for fundamental flame study including soot generation, for instance.

Lastly, **Figure 6** directly compares the flame shape at different gravitational values. Flame shape is extracted from the bright edge shown in **Figure 5.** This figure clearly shows the general trend on flame shape, especially, the flame height is almost linearly decreased as the gravity reduced. Oppositely, flame width increases as the gravidity decreases. In lowest gravity in this study ($G = 0.11g$), the flame shape is similar to micro-jet flames[14)], which the effect of the gravity-induced flow on flame is suppressed instead the diffusion transport is relatively pronounced (Re < 1 and Fr >> 1, where Re and Fr stand for Reynolds number and Froude number, respectively). This fact suggests that the present methodology can work for validation study of gravity-related scaling law such as so called *Froude (Fr) or Grashof number (Gr) modeling*. It is also noted that the flame height in axisymmetric configuration is insensitive to the surrounding flow status[15)], suggesting that the present response of flame height under various gravity levels tells the variation of fuel mass flux (less fuel loading cause reduction of the flame height). We will revisit this issue in our future work.

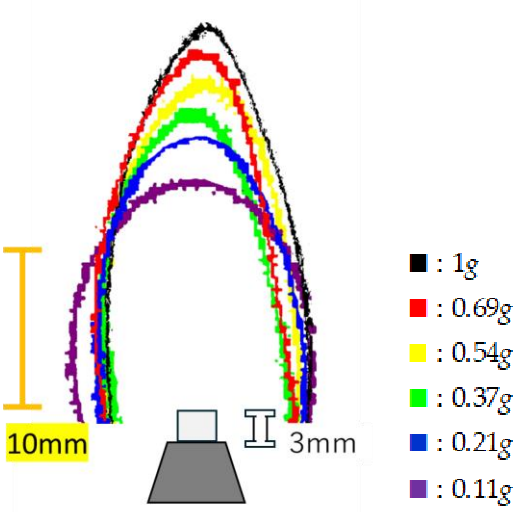

Figure 6. Comparisons of flame shape at various imposed gravity level

4. Remarks

Partial gravity generator using the slope was developed and its feasibility is tested. This time, the protocol is taken as opposite as the previously reported methodology; named "Slope Sliding Method (SSMe)"; namely, the experimental rack is launched along the slope from the bottom then climbing up operation is made. Level of partial gravity, achieved climbing up operation, is controlled by the prescribed slope angle and shows much better than what we have reported previously (original SSMe). *g*-quality achieved by this method is firstly measured and discussed. It is clearly revealed that achieved partial gravity level is sufficiently close to the target (ideal) value. Even the *g*-jitter is presented, the variance is several-order of magnitude smaller than the average. With this, we can safely say that the present method is satisfactory to study overall combustion response subjected to the various partial gravities. As demonstration test, diffusion flame formed over the wick has been adopted for various gravity levels (0.11*g*-0.69*g*), showing that the continuous flame height reduction is presented as the subjected gravity becomes less. Overall, it is ensured that the presently-developed methodology works well for future use in fundamental combustion researches.

References

1) K. Ito: Combustion in Microgravity Environment, Materia Japan, Vol.33, No.8, (1994), pp.1039-1040 (in Japanese)
2) K. R. Sacksteder, J. S. Tien: "Buoyant downward diffusion flame spread and extinction in partial-gravity accelerations", Proc. Sympo. (Int'l) on Combust., Vol.25, No.1, (1994), pp.1685-1692.

3) Y. Nakamura, H . Yamashita, T. Takeno , G . Kushida :" Effects of Gravity and Ambient Oxygen on a Gas-Phase Ignition Over a Heated Solid Fuel". Combust. Flame, Vol. 120, No. 1-2, (2000), pp.34-48
4) S. Takahashi , H. Torikai , Y. Kobayashi , M. Kikuchi , O. Fujita : " Flame Spread Behavior Over a Filter Paper Near Extinction Limit Under Microgravity on the ISS/Kibo", Fire Technol., Vol. 60, (2024), pp.313-334
5) JAXA HP : https://iss.jaxa.jp/education/parabolic/experiment.html (reference date：2024/07/22)
6) N. Yoshihara, A. Ito, H. Torikai: "Flame Characteristics of Small-scale Pool Fires under Low Gravity Environments", Proc. Combust. Inst., Vol. 34, No.2, (2013), pp. 2599-2606.
7) M. Kumagai, S. Arai, Y. Yamashita, M. Suzuki: "Speed-controllable Drop Tower for Low Gravity Experiments", Kagaku Kougaku Ronbunsyu, Vol.20, No.2, (1994), pp. 295-298 (in Japanese)
8) Matsumoto, S. ed.: Living in a Space –From Space Travel to Longer Stay-, Shokabo, Tokyo, (2002) (in Japanese)
9) Y. Akiba, T. Koreki, I. Egami, M. Akiba :"A New Low Gravity Device Applying the Yo-yo Principle", Ez-Space II, J. Space Technol. Sci Vol.25, No.1, (2009), pp.1-9 (in Japanese)
10) Y. Nakamura, K. Sekimoto: "Conceptual Design of Small Partial-G Test Facility: Slope-Sliding Method", J. Japan Soc. Aero. Space Sci., Vol.12, No. ists29, (2014), pp.Th35-Th41.
11) P. V. Ferkul: "Centrifuge in Free Fall: Combustion at Partial Gravity", Proc. 33rd Annual Meeting American Society for Gravitational and Space Research, (2017)
12) A. Z. Lojo, A. Sharma, Y. Liao, M. C. Johnston, P. V. Ferkul: "A Numerical Study of Liquid Fuel Wick Flames in Artificial Partial Gravity in a Centrifuge Facility", Proc. 51st International Conference on Environmental Systems 10-14, (2022), pp. 2-57
13) Spread Across Liquids: The World's First Microgravity Combustion Experiment on a Sounding Rocket, NASA NTRS ID: 20050179434, 1995.
14) H. Ban, S. Venkatesh, K. Saito: "Convection-diffusion controlled Laminar Micro Flames", J. Heat Transf., 116(4) 1994.
15) F.G. Roper: "The Prediction of Laminar Jet Diffusion Flame Sizes: Part I. Theoretical Model", Combust. Flame Vol.29, (1977), pp.219-226.