Conceptual Design of Small Partial-G Test Facility: Slope-Sliding Method

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This work is devoted to propose the concept of the laboratory-scale test facility to provide a partial-g environment based on slope-sliding method, SSMe. SSMe mainly consists of the experimental rack and the less-frictional slope which enable to set at the prescribed angle against the ground. During the sliding operation, the experimental rack should freely “fall-off” in the direction of the sliding so that the normal component of gravity force against the slope surface only remains inside the rack. In this manner, partial-g environment is easily achieved and the target gravity level can be controlled by modifying the slope angle. In this paper, the simple demonstration was performed to verify this methodology works by using the small diffusion flame as the convenient gravity sensor. Several issues including engineering design are discussed in order to address the problems to be managed in future.

Key Words: Partial Gravity, Test Facility, Slope-Sliding

Nomenclature

\begin{align*}
F & : \text{force, } \text{N} (= \text{kg m/s}^2) \\
G & : \text{gravity acceleration, m/s}^2 \\
G_0 & : \text{earth gravity acceleration, 9.81 m/s}^2 \\
Gr & : \text{Grashof number (ratio of the buoyancy to viscous force)} \\
L & : \text{characteristic length, m} \\
M & : \text{mass, kg} \\
P & : \text{characteristic pressure, Pa} \\
U & : \text{characteristic velocity, m/s} \\
\mu' & : \text{coefficient of kinetic friction} \\
\nu & : \text{kinematic viscosity, m}^2/\text{s} \\
\theta & : \text{slope angle against the ground, deg.} \\
\theta' & : \text{flame inclined angle, deg.}
\end{align*}

Subscripts

\begin{align*}
d & : \text{drag} \\
f & : \text{friction} \\
n & : \text{normal}
\end{align*}

1. Introduction

1.1. Need of partial gravity test

A need of test facility to provide the partial gravity environment, where $0 < G/G_0 < 1$ ($G_0$: earth gravity acceleration $= 9.81$ m/s$^2$), has been paid much attention recently due to the variety of practical and scientific demands. From practical point of view, providing the exactly same gravimetric environment as outer planet (e.g., Moon or Mars) can be very useful for the successful space exploration missions in variety of aspects, such as medical and physiologic, and engineering design (e.g. NASA’s Active Response Gravity Offload System (ARGOS)). From the practical point of view, on the other hand, it is also quite attractive to gain better knowledge about the precise gravity effect on physical processes of interests. In fact, a number of fundamental and applied studies have been made to date by utilizing the existing microgravity facilities, such as drop tower, parabolic flight, sounding rocket, orbital experiment in space (e.g., space station) in order to identify the gravity effect on interesting phenomena. It is true that the direct comparison between two extreme cases (normal gravity vs. microgravity) could tell us important issues related on the gravity, nevertheless, it is also true that this is not enough to answer the following simple question entirely; how gravity come to play on the phenomena of interest?. For instance, the sensitivity of the gravity on the target phenomena cannot be known, which should be necessary to obtain the best engineering design to have the demanded partial gravity environments as described. In addition, if the facility to obtain the partial gravity is easy-to-use for everybody, it is even better. This is our motivation in this study.

1.2. Potential alternative methods to study partial gravity phenomena

There exist several potential alternative methods of partial gravity experiment, namely, numerical approach and use of scale modeling concept. Based on former approach (numerical experiment), it is straightforward to play with gravity term numerically to see its effect on the phenomena of interest. Generally, certain assumptions are necessary in order to perform numerical experiment so that the validation study is essential and the quantitative accuracy should be carefully checked. Experimental results performed under normal and/or microgravity have been used to validate the applied numerical model. However, strictly speaking, even though the validation is satisfactory done under two extreme conditions such as under normal gravity and microgravity, the model is not validated under the partial gravity unless the corresponding evidence is available. With this regards, test
data performed under partial gravity is inevitable and the need of the facility to provide such extra-ordinal environment on earth (not in space, where is rather “general” instead) is, therefore, necessary. The latter approach (use of scale modeling) is the way to obtain the similar physical processes experienced under partial gravity field by adopting the accessible condition under normal gravity (without adopting the gravity-managing facility). In other word, even under normal gravity, some tricks are introduced in order to reduce the effect of buoyancy as compared to the others on purpose. One example is to utilize the low pressure to a small flame, which can be the “scale model” of partial gravity flame (for the details see references 9,10) and Fig. 1). Taking advantage of the fact that the transport process tends to be governed by Grashof number ($Gr = GP^2L^3$) under certain condition (likely burner flames, small fire), target $Gr$ under partial gravity can be similarly provided by reducing the size ($L$) and the reducing pressure ($P$) without manipulating gravity, $G$. Although this sounds interesting as alternative way, again, the real partial gravity test data is lacking to validate whether this alternative approach is really satisfactory or not.

![Fig. 1. Example of the flame spreading over thin electric wire under various pressures under normal gravity][10]. Top shows the direct photos, whereas the bottom shows backlight images. As reduce the field pressure, flame shape approaches to round and slightly wider, which looks similar to one observed in microgravity.

### 1.3. Objective of this paper

As summarized above, it is no question that we need a convenient facility to obtain partial gravity environment in order to fulfill those demands as addressed. Actually, we do have several existing technologies to provide partial gravity field (we will deal this in later), however, the present demands prove that the amount of comparable data obtained by those facilities are not enough. Most of the current problems are caused by the handiness and less-controllability. In this regards, epoch-making idea and technology to provide the partial gravity environment is valuable. In this paper, we propose very simple yet having sufficient advantages beyond the existing methodologies to provide the partial gravity environment in small-scale. In the following, the basics of existing partial gravity facilities are briefly summarized and our idea is then introduced. Simple demonstration is performed and further issues to be concerned are discussed.

### 2. Existing Partial Gravity Facilities: Their Merits and Demerits

Not likely the currently-available microgravity facilities as described above (drop tower, parabolic flight, sounding rocket, space experiment etc.), facilities which enable to provide the partial gravity environment is rather limited. Roughly it could be classified into two categories: one is based on the flight experiment and the other is based on the ground experiment.

#### 2.1. Parabolic flight

Most popular way should be to utilize the parabolic flight. The expert pilot can control the pathway to achieve long-range partial gravity during the flight operation. In reality, currently-available reduced gravity data have been obtained by parabolic flight experiment, suggesting that this methodology should be solid and dependable.

![Fig. 2. Mean-square value of partial gravity data obtained by parabolic flight experiment provided by DAS (courtesy of JAS and JAXA). Pump up gravity prior to entry of parabolic test was suppressed by 1.3 $G_0$.][11]

In Fig. 2, actual acceleration record given by parabolic flight are shown (courtesy of Diamond Air Service: DAS and JAXA). From this figure, it is clear that sufficient time of the target partial gravity is available. If one needs more time for partial gravity, it is possible to adjust by increasing the pump up gravity prior to the entry (~ 2.0 $G_0$). Obtained partial gravity tends to be (slightly) fluctuated in time, so-called g-jitter, which is impossible to eliminate entirely. Only the demerit of this method is costly and not so convenient. It is worthwhile to note that obtaining higher partial gravity environment (e.g., 0.5 $G_0$ for example) looks rather difficult as compared to the smaller ones. This fact implies that the holding the controllability and quality of prescribed partial gravity would be quite difficult.

#### 2.2. Utilizing centrifugal force

One famous and excellent idea to provide the partial gravity environment is based on combination of centrifuge technique with any type of microgravity facility. Since centrifuge system can provide the wide range of centrifugal force continuously so that wide range of various gravity levels can be realized. This concept sounds ideal in the manner of controllability and quality of the target partial gravity level, in fact, this concept is the one originally proposed for “partial gravity compartment” designed in space hotel [12]. However,
the size of facility becomes relatively large and heavy, resulting that this idea is hardly utilized as one of productive partial gravity test facilities with authors’ best knowledge.

2.3. Ground experimental facility: drag-force controlled

Other methodologies have been developed by installing the additional function into the drop tower (microgravity) experiment in order to control the drag force of the falling experimental rack, for instance, by utilizing counter-weight\(^1\),\(^2\). The target of these facilities is basically to provide easily the acceptable partial gravity environment, although the time for the partial gravity is limited (this is advantage of this methodology). In Fig. 3, typical example of counter-weight style partial gravity facility is shown.

Note that the counter-weight based facilities need the pulley to hang the rack and the wire to hang it from the ceiling is firm enough to consume energy as wire deforms. In addition, the pulley is exposed to sufficient friction with the wire during the falling operation. Considering altogether, even no counter-weight is operated, the rack is not freely falling-off, rather, the friction/restraint may remain as the drag force to the falling rack. Hence, residual gravity always exists so that the gravity level below the residual one is hardly achievable. For example, above-mentioned experimental facility developed at Hirosaki University is not able to achieve the less than 0.3 \(G_0\)\(^1\).

Other issue is slowing down mechanism. Drop tower facility needs certain length in vertical direction to slow down the falling rack. Thus, the entire height of the facility cannot be effectively used to obtain the partial gravity. Although this system sounds technical, these limitations (hanging structure, longer vertical length) should be recognized as demerits.

2.4. Other ground experimental facilities

There are other ground-based facilities to achieve the controllable partial gravity environment beyond the conventional counter-weight style. One example is so called acceleration-controlled concept\(^3\),\(^4\), which controls the motion of the experimental rack by changing its acceleration to obtain the prescribed gravity environment. Example system is shown in Fig. 4. The experimental rack mounted over the belt is connected to the servo motor. The belt is moved by force with the prescribed acceleration operated by the motor. This allows us to “create” any level of acceleration, namely partial gravity, as long as the motor can provide such prescribed acceleration satisfactory. External force given by motor should compensate the kinematic energy for deforming belt and other (frictional) force so that it could give an excellent controllability performance.

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Fig. 3. Counter-weight style partial gravity generator facilitated at Hirosaki University (courtesy of Profs. Ito and Torikai)\(^5\). (a) Hirosaki U’s c partial gravity generator (b) Achievable gravity

Fig. 4. Acceleration-controlled style partial gravity generator developed by Kumagai et al.\(^6\). Top is the conceptual design for the facility and the bottom is the measured gravity obtained by this method (target gravity is 0.2 \(G_0\)).
According to Ref. 16, achievable lower gravity can be less than 0.3 $G_0$, which would be hard to obtain with counter-weight style as described. Nevertheless, the vertical length issue should be remained (as long as the rack is dropped down vertically) also somehow hanging structure also essential.

Other unique concept is yo-yo style facility proposed by Akiba et al. since 2005\cite{17-20}. This idea practically sounds and mechanically be interesting. Not likely others, the main motivation of this concept is to reduce the size of the facility to make it handy and convenient. Generally the accelerating motion of the experimental rack of partial gravity facility needs the sufficient length to slow down. If one makes it shorter, sufficient counterforce is experienced to the rack during the deceleration operation, resulting in destroying the experimental devices equipped in the rack. By introducing yo-yo mechanism, those problems are essentially avoidable, yet longer partial gravity time can be expected by its reciprocating motion during the operation. In this way, the total size of the facility is reduced and the facility is easy to install anywhere. Because this facility includes special features in the pulley (patented by Akiba et al.), the technique is not purely opened to everybody.

As summarized, all existing facilities have both definite merits and demerits. Considering as the lack of partial gravity data, the main merit should be its convenience and ease to introduce: it allows many researchers to involve on topics with partial gravity. On the contrary, major common demerits are the necessity of sufficient vertical length (as pointed by Ref. 17-20) and hanging structure. Our main concern is to avoid these demerits with holding the merits as shown above. Especially once we can avoid hanging structure, no massive mechanical part exists on the top of the facility so that the foundation construction for this purpose can be avoidable. This makes more handy and easy in installation of the facility to anywhere necessary.

3. Our Proposed Method: Slope-Sliding Method (SSMe)

Our proposed method to generate the partial gravity is very simple without having any hanging structure. Basic concept is schematically shown in Fig. 5.

Fig. 5. Schematic illustration of the concept of slope-sliding method (SSMe).

Slope-sliding method (SSMe) mainly consists of the sliding experimental rack over the specific angle of the slope. Assuming that there is no friction between the rack and slope, the horizontal component of acceleration against the slope becomes zero, thus the normal component of the acceleration to the slope surface (inclined) is only effective during the sliding event. In this way, partial gravity environment can be easily obtained inside the rack (see figure embedded in Fig. 5). Since the factor of the normal component of the gravity acceleration toward the surface is $\cos \theta$, where $\theta$ denotes the slope angle, any partial gravity environment can be obtained as long as the angle of the sliding slope is properly controlled. SSMe has the following (at least) three features beyond the existing partial gravity facilities as explained above. One is that the fine (continuous) control of the level of partial gravity is possible by changing the angle of the slope, the second is that the gentle stopping of the sliding rack is possible by adopting the horizontal longer path, not vertical one to avoid any vertical construction, the third is that the facility is based on the self-standing feature so that no hanging structure is necessary to prevent the additional foundation construction to install it. Combine all advantages pointed here, this methodology becomes unique and effective.

4. Demonstration of SSMe

4.1. Experimental setup

Simple demonstration adopting SSMe is carried out to prove whether this methodology works satisfactory or not. Considering the partial gravity time is quite limited, the gaseous diffusion flame is selected as the target object to be investigated since it can readily respond to the imposed gravity field.

Fig. 6. Schematic illustration of the demonstration test employed in the present study. Left: burner, right: image during the sliding operation.

Fig. 6 shows schematic illustration of the burner and image during the sliding operation. A conventional spirit lamp (120 mL standard type: bottom part is 71 mm diameter made by glass) is employed to form the target diffusion flame. The 5 mm width of cotton towel is used as the wick and its projection length over the port is adjusted in order to have the best size of flame for the present purpose (35 mm of flame height as shown in later). Liquid fuel used here is mainly acetone and small amount of decane is doped in order to receive enough luminous intensity from the flame (e.g.,
radiation from the hot soot particle). Typical steady diffusion flame, which is quite sensitive to the buoyancy-induced flow, is formed over the wick. To avoid any disturbance from the air side, outer (glass) tube with sufficient height is surrounded over the lamp as shown in Fig. 6. The metal mesh is placed at the top open end of the tube to hold the stability of the object (flame) from outer disturbance. PMMA board is used for the sliding slope. Chalk power is spread over the surface in order to reduce the kinetic friction during the sliding operation. Angle adjusted for the present demonstration is fixed at 30 degree.

Flame height adjusted is about 35 mm for the present purpose. Assuming that the fuel velocity vaporized from the wick is 50 mm/s, and kinematic viscosity is about 150 mm²/s, then the calculated Reynolds number \( Re = \frac{UL}{\nu} \) where \( U \) is characteristic velocity, \( L \) is characteristic length and \( \nu \) is kinematic viscosity and Froude number \( Fr = \frac{U}{(GL)^{0.5}} \) based on the flame length \( L = 35 \) mm are 11.7 and 0.085, respectively. This implies that buoyancy force is more than 10 times larger than the inertia force, and the inertia force is more than 10 times larger than viscous (diffusive) force, hence, the buoyancy is dominant force to drive the transport processes in this system so that its effect on the flame shape should be enormous. In other word, the target flame in this study should properly work as “gravity indicator”.

Flame shapes are taken by high-speed imaging system (Casio EX-F1, frame rate: 300 fps) fixed on the ground. Prior to the productive runs, several preliminary tests were performed to adjust and optimize the shooting conditions. The timing of sliding is manually controlled (held/released by hand) since the time elapsed is not the main concern here. Reproducibility and stability have been well-checked to ensure that the obtained results are quite solid.

4.2. Results and discussion

Fig. 7 shows the typical flame images taken prior to the sliding operation (stationary condition). It is readily understood that the flame tip points toward the vertically upward against the gravity, implying that this is the only acceleration the object (flame) feels. Of course the angle against normal to the sliding slope and flame axis is identical to the slope angle, \( \theta \). Since the no surface treatment was made to the glass tube, reflected image of the flame by the surrounded wall appears in the image.

Once the holding hand to the lamp fixed is released, the lamp smoothly slides down along the plate with angel of 30 degree (against the horizontal ground). Fig 8 shows the high-speed imaging results to identify how the flame feels the acceleration during the sliding operation. It is readily understood that the sliding flame is quite solid and no fluctuation is identified during the sliding operation. Obviously the angle of the flame tip pointed is not identical to the one prior to the sliding operation (stationary condition). The flame tip pointed toward between the vertical (to the ground) and the normal to the slope surface, revealing that the gravity acceleration component toward the sliding direction is reduced during the sliding operation.

Direct comparison of these flame images is made in Fig. 9. Note that these images are adjusted to be the same magnification so that direct comparison is possible. As results, the following major differences are identified clearly, namely, the flame tends to becomes wider (flame width), a bit shorter (flame height), and brighter (luminous intensity increases) during the sliding operation as compared to the one shown under a stationary condition. Importantly all three
features can be the evidences the sliding flame is subjected to lower gravity field, suggesting that the present methodology simply works.

Flame height behavior observed here is somewhat opposite to the feature of gaseous jet flame; such as the flame height becomes elongated under reduced gravity environment. This is reasonable since the present flame is not jet flame (you can fix the flow rate of fuel), but the flame formed over the wick (you cannot fix the flow rate of the fuel). Flame height is mainly controlled by the amount of loaded fuel and vaporization speed of the fuel from the wick depends on how the flame gets closer to the wick to enhance the evaporation. As the gravity reduced, the distance from the flame to the wick would be slightly larger so that the heat flux from the flame to the wick decreases, namely, the flame vaporization speed decreases accordingly. Indeed, the size of the flame is not large enough, the radiation heat transfer is believed to be negligibly small. In this way, the flame could become smaller as the lower gravity is employed.

4.3. Further issues to be considered

As noticed, concept of SSMe is nothing complex and very simple hardware is necessary, it is easy to combine other technologies to upgrade the system. Here are some problems to be considered further and tips to resolve them.

One bottle neck issue of SSMe is the need of the least frictional surface as the sliding plate (or rail as substitute). Obviously there exists no such ideal one so that all technologies should be introduced to resolve this difficulty. There are (at least) the following two candidates for this purpose; one is introducing the special treatment over the surface to enable to attain such ideal condition and the other is compensating the prescribed frictional force as made in Ref. 16. There are a variety of technologies potentially applicable to cover the former one. For instance, air-curtain (air-slider and air-bearing etc.) and magnetic levitation should be attractive ones to be adopted. The latter candidate sounds simpler to apply since the frictional force should be already known so that we know the target to control. Let us consider how to find it by using the example as shown above. In the demonstration test, because of the non-zero value of surface friction, $\theta'$ shown in Fig. 8 cannot be zero. Considering the actual condition, force balance should be depicted as follows in Fig. 10.

From the force balance during the sliding operation, the following relation should be given as

$$\tan \theta' = \frac{F_f}{F_d} = \mu' \frac{MG_0 \cos \theta}{M G_0 \cos \theta} = \mu'.$$

(1)

Considering $\theta'$ obtained in the demonstration test is 10 deg. (measured), current $\mu'$ can be calculated as 0.176. By utilizing general lubricants, it could be reduced to the half ($< 0.1$) so that it is easily upgraded. To make it zero by force, we can pull the rack during the sliding operation with the controllable force, $F_d$, namely,

$$F_d = \mu' MG_0 \cos \theta.$$

(2)

One wishes to reduce $F_d$, the reduction of $\mu'$ and $M$ is the key and this is achieved by design of the experimental system. Drag force, $F_d$, can be adjusted when the slope angle is modified. By using motor to control the drag force as similar to Ref. 16, it should be acceptable.

Furthermore, to avoid any jitter during the sliding operation, posture of the sliding rack should be well-controlled without causing any perturbation. By taking advantage of the enough area surface (i.e., bottom surface of the rack) to manage this issue, we should have variety choices to fight with this difficulties, although this is still opened to question and need to be resolved eventually.

Sliding rack should be avoided to fall-down during the sliding operation. For this purpose, the shape can be a trapezoid (broadened toward the bottom). This allows more contacting surface of the rack to the sliding surface so that adjustment of shape and surface friction management should be considered simultaneously.

Prior to the final stage (slowing down the sliding rack), the rack must be diverted to be horizontal and this process should be done smoothly. Some additional considerations on this point should be made in near future.

Lastly, SSMe needs the sufficient length horizontally for slowing down the sliding rack, which should be more practical as compared to the additional vertical space in the lab just for the post-process purpose. This could be either merit or demerit according to the environment which users have. Generally, the reduction of slowing down length is difficult and costly. Instead, although we need to introduce additional technologies to handle the sliding path issue (divert from angled to horizontal), it would be more handy and less-costly. Since the most of gaseous combustion studies do not need longer partial gravity environment and the burner can be smaller and lighter, SSMe concept may work properly and effectively.

5. Concluding Remarks

In this paper, we present the conceptual design of small test facility to provide a partial gravity environment in laboratory scale based on slope-sliding method, SSMe. Demonstration of SSMe is performed by utilizing sliding diffusion flame (by lamp) to ensure that SSMe works in a simple manner. Merits and demerits are discussed, then further improvements are
reviewed. We are now working on the scale-up of test facility based on SSMe, and further report will be available in future.

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