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相似則を活用した微小重力下での燃焼場の再現

Impact of Scale Model Experiment for Simulating a Microgravity Flame

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1. Introduction

A having microgravity (or reduced-gravity) flames is not an easy task because there needs special facilities/hardware depending on the achievable microgravity time [1)]. Suppose that daily or hourly microgravity time is mandatory, applying the space experiment is only choice. Several minutes of microgravity time would be brought by sounding rocket experiment. Several-tens seconds are offered by the parabolic flight experiment. Several seconds are available by drop-tower experiment. Having the opportunity to perform such microgravity experiment with flying objects (e.g., space station, sounding rocket, parabolic flight etc) is rather limited, yet ones need to pay the suitable cost to use such special flying object for your specific purpose and need to wait until the chance to come. In general, space experiment needs to wait years to launch and approximately costs around hundreds million JPY (although depending on the type of experiment and who will support, though) [2)]. Similar time is needed to perform sounding rocket yet the cost will be less than half of the space experiment. Parabolic flight can reduce time much (potentially within a year) and the cost could be half of the sounding rocket, however, you must give up the quality of the achievable gravity [3)]. Droptower experiment is the most convenient for the time and cost (less than million JPY in general), in case that the achievable microgravity time is acceptable for your experimental design [4)]. In addition, there is another severe limitation for test volume and available power which makes difficult the precise measurements due to the limited selection of the hardware. Having partial gravity condition is further limited in terms of the available facilities [5)]; potentially it will be offered by parabolic flight (with negotiation), or using special-type droptower with fine control of the counter weight, sliding slop method [6)]. Afterall, all reduced-gravity projects must accept such severe limitations (in chance, time, space, power, cost) to obtain scientific outcome.

Although this is true and we must accept those limitations always, there is the room to consider to have “alternative” methodology to investigate the microgravity features under “simulated” microgravity environment. In this report, we would introduce the concept of scale modeling in order to propose the alternative methodology to simulate the phenomena observed in microgravity condition and show its effectiveness even in quantitative discussions. A example target is combustion of solid polymer which has been extensively studied in the past microgravity projects in space agencies.

2. Design Concept

2.1 Scaling Law

Original concept to simulate the space fire using scale model experiment has been proposed by Nakamura and coworkers [7], although they simply introduce the concept and less evidence with quantitative accuracy. This report would touch this point to show the effectiveness on this concept. Based on the previous work, when we would like to simulate the combustion field with extremely weak flow under the microgravity, Grashof number similarity would work to propose the scale model experiment. Let us recall the concept briefly as follows:

$$Gr = \frac{\rho^2 G \beta \Delta T L^3}{\mu^2} \sim L^3 G^1 P^2 \quad \text{.......(1)}$$

Here, ρ is density [kg/m^3], G is gravity acceleration [m/s^2], β is coefficient of volume expansion [-], ΔT is temperature difference between flame and ambient [K], L is representative length scale [m], and μ is coefficient of viscosity [Pa s]. Taking into account the equation of state, density is linearly correlated to the pressure ($\rho \sim P$). Eventually, the dependency of representative quantities (such as L, P, G) on Gr can be expressed as $L^3G^1P^2$, as indicated in Eq.(1). Readily, to achieve reduced gravity condition (namely, low-Gr condition), an applying small scale with low-pressure without managing gravity found to be the alternative way as long as the target process is truly governed by Gr. Of course that the pressure cannot be extremely small because our interest here is flaming condition. Therefore, the suitable choice of the length scale is required to achieve low-Gr at normal gravity environment to simulate microgravity condition. In other word, if we pay attention to design the scale model experiment, it is physically possible to reproduce the microgravity flame without any reduced gravity facilities, accordingly, we do not need to consider severe limitations as listed above.

2.2 Target and Experiment

In order to validate the scale modeling concept on polymer combustion, let us target the spherical 1-D flame formed over the polymer sphere because of two reasons; one is that there is well-known "d-square law" and theoretical expression is possible to identify the burning character, and the other is that there is existing microgravity data provided by NIST [8,9] in order to validate directly to identify the impact of the presently-proposed methodology.

Experimental apparatus used in this study is shown in Fig. 1; schematic illustrations are placed in the left (a)(b) and the direct photo images are allocated in the right (c)(d), respectively [10].

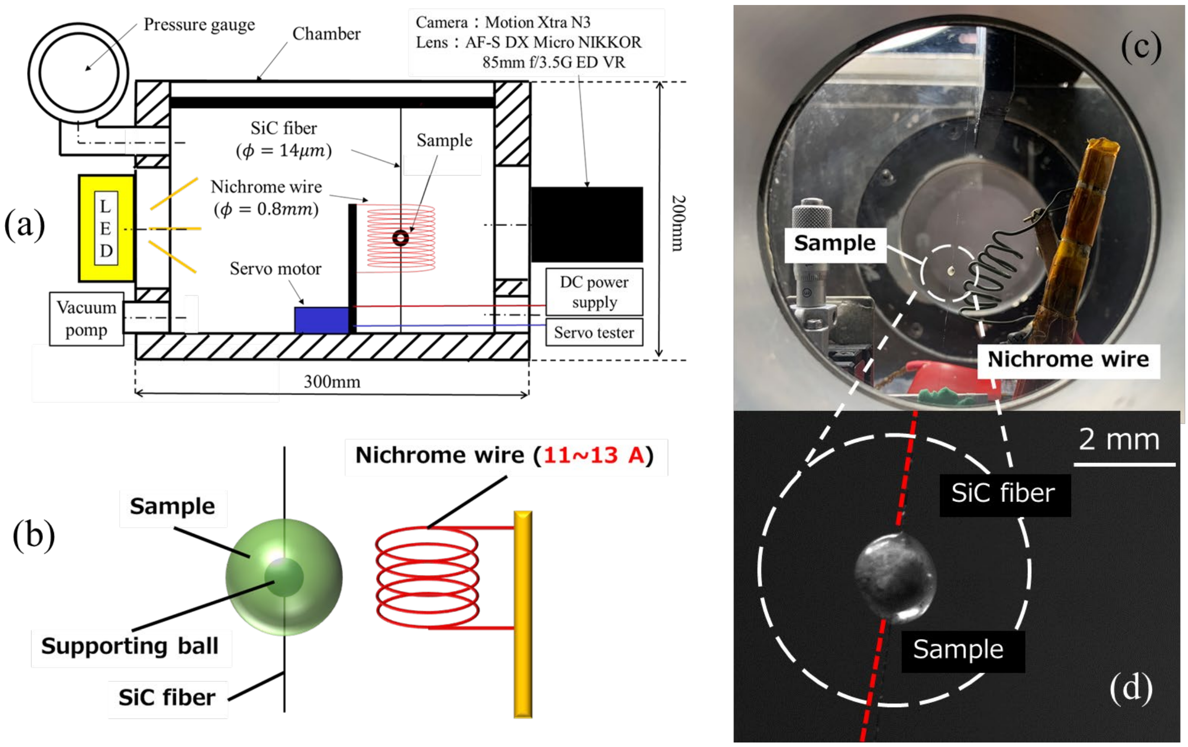

Fig. 1 Experimental apparatus. (a) schematics of whole system, (b) magnified illustration of burning specimen, (c) direct image from the view port, (d) magnified picture of the burning specimen.

The entire test is operated in a vacuum combustion chamber, whose inner dimension is 365 mm (L) x 260 mm (W) x 180 mm (H). It is equipped with a pair of quartz windows to allow observation of the entire event inside the chamber. LED light mounted outside the chamber is adopted to provide the backlit image during the burning event. CCD camera (Motion Xtra N3. 1280x1024 pixel) with Nikkor lens is set to visualize the burning process at 50 Hz. A burning sample is suspended by a thin SiC fiber (Hi-NicalonTM made by Nippon Carbon co ltd., 14 μm in diameter) vertically oriented by jigs as shown in the figure. Ignition is induced by a manually-designed nickel-chrome wire (gauge diameter is 0.8 mm). Applied current is adjusted based on the condition. The location of the heating device can be controlled by a servo motor and timing is programmed to maintain reproducibility. Internal pressure is set at 20 kPa, 50 kPa and 100 kPa by manually controlling the valves. Composition of ambient gas is set to either 20 or 30 vol.% of oxygen diluted by nitrogen and gas temperature is at room temperature. During the burning event, the chamber is totally isolated, and no external gas flow is presented. Ignition operation imposes after several minutes after the mixture loading process to ensure the ambient gas is satisfactorily quiescent. Once a successful ignition is observed, the heating device is removed to avoid any effect on the subsequent burning event. To ensure repeatability, the test was undertaken at least 5 times.

Burning specimen (sample) is PMMA sphere which has been prepared from small slab of the PMMA sheet. PMMA slab is initially placed over the ceramic porous ball (supporting ball in the figure) whose diameter is around 0.5-0.6 mm and porosity is around 0.31. By adopting the sufficient heating yet insufficient to burn, molten layer was successfully covered over the ceramic ball as shown in Fig. 1. Outer diameter of the test specimen is around 1.5-1.6 mm depending on the sample preparation operation.

3. Results and Discussion

3.1 Appearance of Low-P Flames

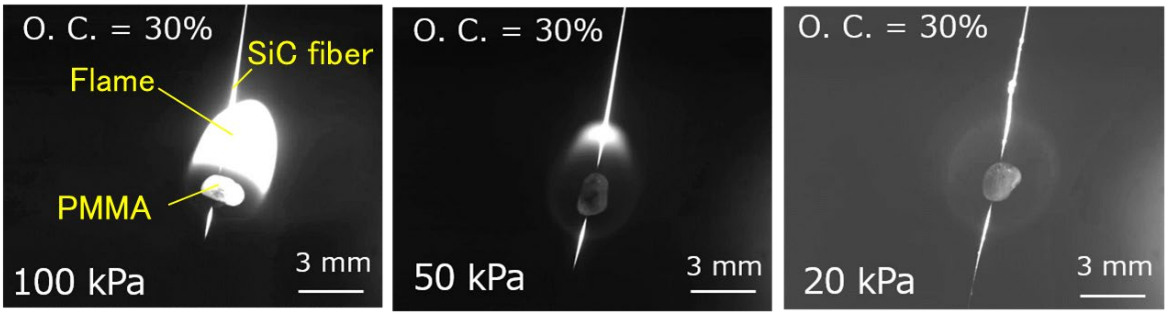

Fig. 2 Typical still flame image under various ambient pressures (oxygen concentration is 30 vol.%)

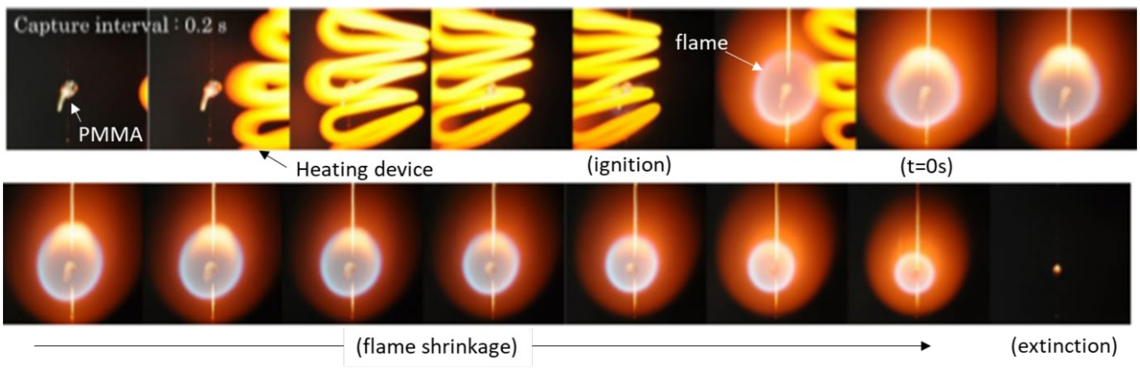

Fig. 3 Typical time sequence from ignition to extinction of flames formed under 20 kPa with 20 vol.% of ambient oxygen concentration. Time interval is 0.2 s.

Fig. 2 shows the typical (still) flame images formed under various low pressure condition. At normal pressure (= 100 kPa), the flame exhibits typical "tear-drop" shape elongated toward upward due to the buoyancy induced flow. Strong luminous part is identified over the burning sample, indicating the soot formation is presented. As reduced the pressure to the half (50 kPa), luminous sott zone is dramatically reduced and the flame becomes a bit wider as compared to what observed in 100 kPa. Such feature is more prominent when the pressure reduced to 20 kPa, showing nearly "perfect" spherical non-sooting flame is observed. Interestingly, SiC fiber as suspender of the specimen exhibits highly luminous especially over the flame (upward location)/ This is because, again, the buoyancy induced flow is presented and it is enough to heat up the fine SiC fiber there. This fact clearly suggested that the buoyancy flow is clearly presented, although the flame stays spherical shape under low-pressure environment. Such feature is clearly identified the time sequence color images as shown in Fig. 3. Although the blue flame exhibits spherical shape, outer hot gas emission (in red, potentially caused by radiation from water vapor in high temperature product gas) clearly deforms/elongated toward the upward due to the buoyancy.

In this way, obviously we did not eliminate the buoyancy from the combustion system, however, we could "comparably reduce" buoyancy effect within the scale of the flame zone. This is achieved by adopting the small specimen, namely, selecting the appropriately small characteristics length scale, *L*. Afterall, it is qualitatively said that adopting the "proper" combination of small-*L* and low-*P* to simulate low gravity flame without manipulating the gravity and Grashof number similarity would hold. Next, we shall investigate whether the quantitative accuracy by comparing with the available microgravity flames formed over the spherical PMMA [8,9].

3.2 Observed Burning Rate

According the droplet burning theory, well-known "d-square law" should be observed when 1-D burning structure is fulfilled. Eqs. (2) and (3) are

$$-\frac{d(d^2)}{dt} = 8a\left(\frac{\rho_g}{\rho_l}\right)\ln(1+B) \quad \text{....(2)}$$

$$d(t)^2 = {d_0}^2 - Kt \quad \text{....(3)}$$

Here, $d(t)$ is diameter of the burning specimen [m], a is thermal conductivity [m^2/s], K is burning rate constant [m^2/s], t is the elapsed time [s] and B is transfer number [-] initially proposed by Spalding [11]. Subscripts of 0, g and l stand for initial state, gas and liquid (molten phase), respectively. Theory clearly claims that the burning rate constant is recognized as a kind of "material constant (under the prescribed condition)" and directly related to the transfer number, which presents the burning character in the prescribed environment.

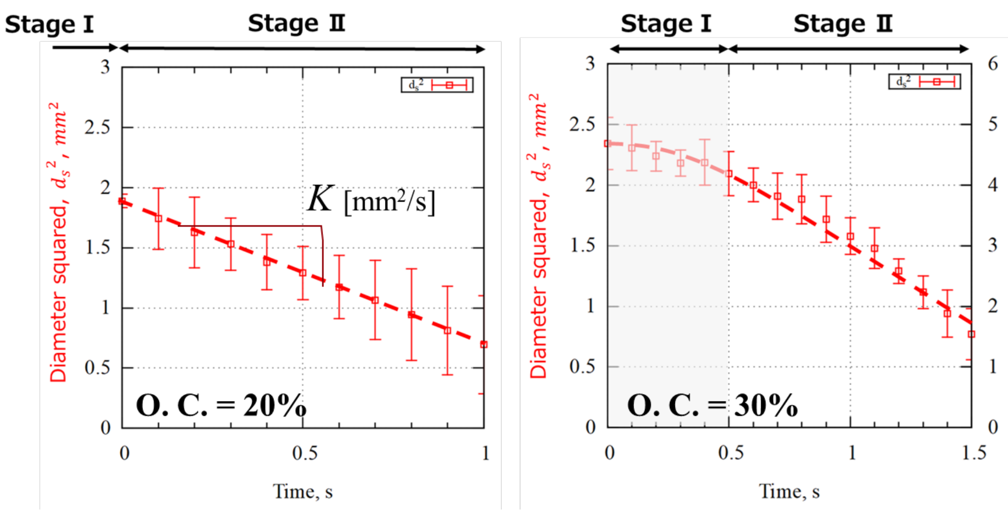

Fig. 4 Evidence of d-square law for 20 kPa PMMA flames observed in this study.

Fig. 4 exhibits the how the d-square (d^2) changes in time for the low-pressured cases (20 kPa) at various oxygen concentrations. Obviously d-square decreases linearly with the elapsed time, confirming that d-square law is preserved. It is noted that in early stage stated as "Stage I" in the figure, the change is rather gentle. This is mainly due to the volume expansion of the specimen. In general, density of the molten phase is 10 % lower than the original (solid polymer, implying that the volume expansion shall occur until the thermally quasi-steady state is achieved. In this regard, Stage I is considered as the transition period to reach the quasi steady state. Hence we shall consider the following Stage II is suitable to characterize the burning rate constant, *K*, as shown in the figure. Error bar is added in Fig.4 to indicate the reproducibility. Although error seems to be large, it is smaller than that of higher pressure, likely 50 kPa and 100 kPa in this study. At higher pressure, the bursting of the bubble formed inside the molten layer (due to the internal gasification process) is frequently observed and causes the large fluctuation of the observed data. The bubble bursting is promoted especially in lower half of the specimen where the flame is getting closer to provide higher heat flux locally. Similar bursting behavior is frequently found in microgravity experiment performed by NIST [8,9], where the PMMA sphere burnt using parabolic flight experiments (see Fig. 5).

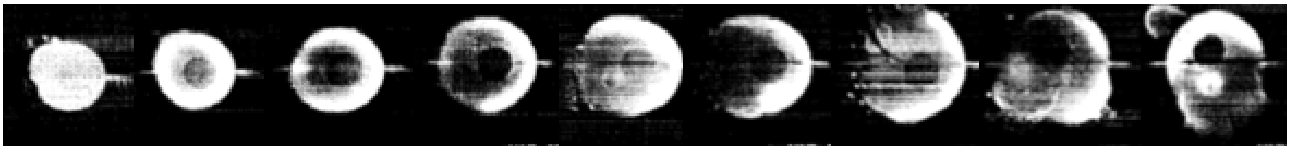

Fig. 5 Time sequence of burning PMMA sphere in microgravity (referred from Ref. 8)

As shown in Fig. 5, small dots are frequently ejected from the specimen and the flame shape is deformed accordingly. Because the bubble bursting is caused by the gasification inside the molten layer, occurrence would be controlled by the size (more importantly, thermal layer thickness) of the burning specimen. In our study, as described in Fig. 1, PMMA layer thickness is "controlled" due to the presence of ceramic (porous) ball at core of the specimen. Such layered structure would be quite powerful to suppress the bubble formation and data fluctuation due to its bursting. Measured burning rate constants, *K*, for previously-reported microgravity experiment [8,9] and the presently-proposed scale model experiment are summarized in Table 1.

Table 1 Comparisons of burning rate constant (K)

	This study (P = 20 kPa)	Reduced-g*
O. C. = 20%	1.38±0.334	1.3
O. C. = 30%	1.78±0.179	1.8

* referred from [8,9]

As clearly shown in this table, there is quite good agreement between two experiments, implying that the scale model experiment based on *Gr*-scaling works quite well to simulate the burning character observed in microgravity not only the qualitative but also the quantitative sense. Since the presently-proposed scale model experiment only needs the (large) pressure controlled chamber and there is no (larger) size limitation in volume (of course certain testing volume is necessary to achieve the pseudo steady-state burning condition, though). Various kind of optical access is technically possible and many runs are allowed to ensure reproducibility. Although there needs to check the "proper" combination of the size and pressure to be investigated, it is well confirmed that the scale model concept work quite well in combustion in space.

4. Concluding Remarks

Grashof-scaling concept is introduced to simulate the microgravity flame behavior and it is successfully revealed that the concept works quite well not only qualitatively but also quantitatively. Following advantage shall be drawn by adopting the scale model experiment for combustion researches in space.

- No severe limitations (testing time, testing volume, measurement devices including optical accesses) to investigate the microgravity phenomena precisely on earth.
- Many runs are possible to ensure the reproducibility without extra cost (although extra effort is mandatory)
- Any minor/major modification can be added and upgrading the system accordingly to allow the improvement; which is quite fit to the scientific research, not the project works.

- Pure "blue (no-sooting)" spherical flame is obtained under low pressure to allow to study the effect of soot separately (for instance, adding artificial particle inside the chamber to simulate the effect of the soot under the controlled environment)

Of course there are several issues to be managed well (for instance, should find the proper combination of the scale and pressure to achieve 1-D spherical flame (=basically large scale flame is not possible since Gr-scaling law is no longer available), should prevent the falling-off of the burning specimen during the test etc), it should be emphasize that there is alternative methodology to investigate the featured burning character in microgravity without fancy/costly microgravity facilities.

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