P09

微小重力を活用した PMMA 一次元燃焼

1-D burning character of polymer (PMMA) sphere in microgravity

松本瑠海 [1], Amaryllis Kiwin Wellson[1], 松木大輝 [2], 山崎拓也 [2], 中村祐二 [2],
Rumi MATSUMOTO[1], Amaryllis K. WELLSON[1], Daiki MATSUGI[2], TakuyaYAMAZAKI[2] and Yuji NAKAMURA[2]
[1] 豊橋技術科学大学大学院工学研究科機械工学専攻，Department of Mechanical Engineering, Toyohashi University of Technology
[2] 豊橋技術科学大学大学院工学研究科機械工学系， Department of Mechanical Engineering, Toyohashi University of Technology

1. Introduction

Recently, main players of space development have been taken over by private enterprises from national space agencies. Accordingly, not only the safety management but also the cost reduction to adopt new materials for use in space has been paid close attention. Taking advantage of the excellent properties of polymers (e.g., light weight, high-durability, and high-insulating performance etc.), the use of polymers suited in space use is way to achieve significant cost reductions. On the other hand, polymers are flammable and its flammable characteristics must be well-studied under space environment. According to earlier works done by NIST using parabolic flight [1,2)], it has been notified that polymer burning exhibited the highly complicated processes combined with chemical reaction and non-linear dynamic behavior such as bubble bursting and swelling at heating. This behavior is frequently found in microgravity experiment performed by NIST [1,2)], where the PMMA sphere is burnt using parabolic flight experiments. In their test, the number of experiments was limited to 1-5 times per condition because of the limited test opportunities [3)], which makes difficult to understand the effect of such non-linear dynamic behavior on the burning character although it is well-known that it may vary depending on the imposed experimental conditions (e.g., ambient oxygen concentration and pressure). The purpose of this study is to specially design/organize the test adopted for droptower experiment which investigate such non-linear dynamic behavior. Tests are repeated with satisfactory times to obtain statistical variation of the measured data to extract the feasible trend of the burning character of the PMMA sphere in microgravity.

2. Experimental setup

Throughout the study, spherical-shape of specimen is adopted because of the following two reasons. It would give the simplest (1-D) combustion system under microgravity (buoyancy-free) environment. Once it is done, the burning specimen should follow the “d-square law” to define “burning constant”, which is the candidate of the burning character. A microgravity environment is achieved by 50 m droptower

COSMOTORRE (HASTIC, Hokkaido Aerospace Science and Technology Incubation Center), which can provide us with 2.8 s (effective time is 2.5 s [4]) of free fall. Experimental apparatus used in this study is shown in **Figure 1.**

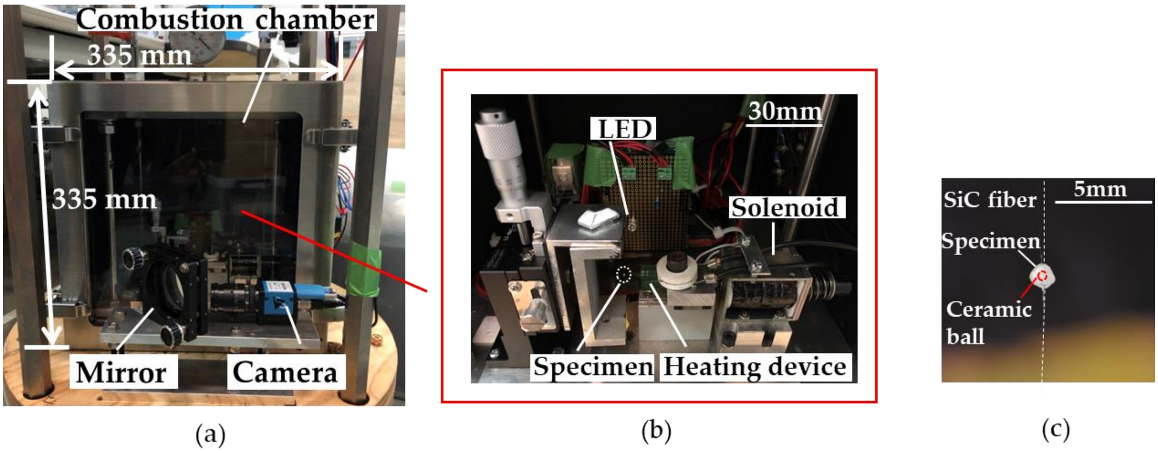

Figure 1. Experimental apparatus, (a) Combustion chamber and visualization devices, (b) Inside the combustion chamber, (c) Magnified picture of burning specimen

The entire test is operated in a combustion chamber, whose inner dimension is W250×D245×H250 mm, respectively. It is equipped with acrylic window to allow observation of the entire behavior inside the chamber. LED light mounted inside the chamber is adopted to provide the backlight image during the burning behavior. CMOS camera (DFK33UX273. 1440×1080 pixel) with macro lens is set to visualize the burning process at 25 frames per second. With flashing of LED light, we can capture the backlight and direct flame image in turns (frame-by-frame). The location of the heating device made by the Nickel-Chrome (NiCr) heating wire is controlled by a solenoid and timing is programmed. Ignition is caused when the heating device contact with the specimen. Ambient condition in the combustion chamber was 0.101 MPa and gas temperature was at room temperature, and 21 vol. % O_2.

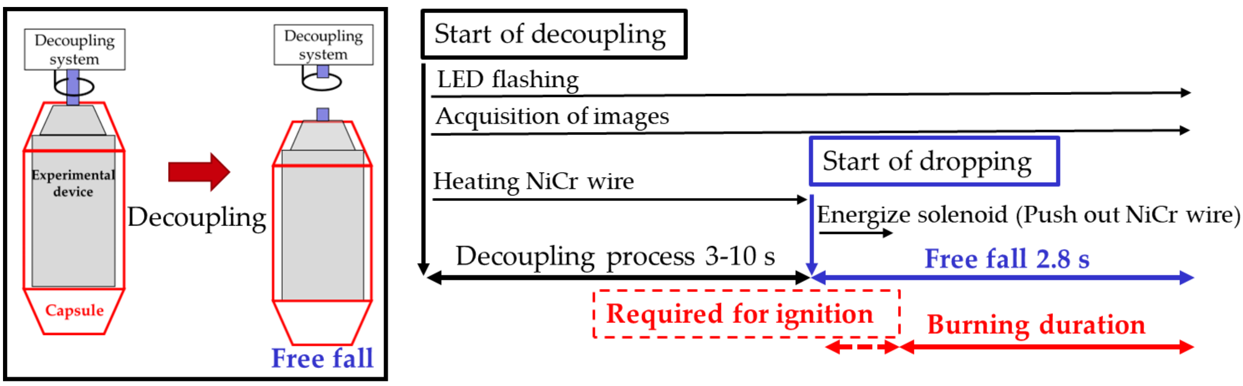

Figure 2. Experimental overview and system time sequence

Experimental overview and system time sequence is shown in **Figure 2**. In the microgravity experiment, heating of the NiCr wire, flashing LED, and capturing images were triggered by the start of the capsule decoupling, and then energizing the solenoid (to push out the heating device) was triggered by the start of the capsule dropping. Flashing LED and capturing images continue from start of the capsule decoupling to the end of dropping. The solenoid is energized for 550 msec which is required for pushing out the heating device to contact with the igniter gel and ignition.

In order to achieve a quick ignition to have the subsequent burning, tiny amount of "igniter gel" was put on the specimen, whose weight is less than 1% of the specimen. Once the ignition operation is proceeded, the gel can catch up a quick ignition to form the gel-oriented-flame over the specimen. Before gel is completely burned out, the PMMA surface can reach to the gasification temperature to form PMMA-oriented-flame. Such transition is smoothly made to avoid excess heating of specimen (to promote deformation) to achieve the flaming of PMMA. Microgravity experiment was carried out 14 times under the same conditions in this study to investigate the statistical feature of the target phenomena to be studied.

3. Results and Discussion

3.1. Appearance of 1-D flame

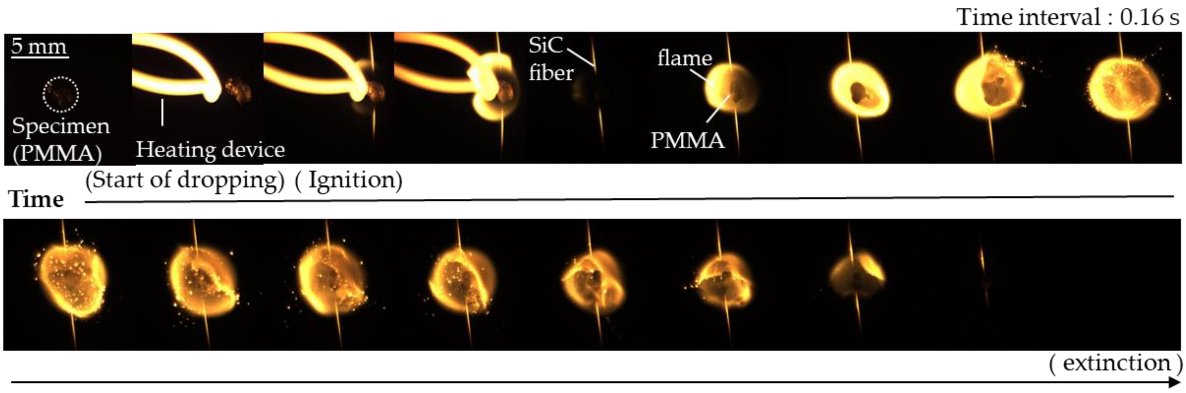

Figure 3. Timely variation of PMMA burning behavior from ignition to extinction in the present microgravity experiment. Time interval for each image is 0.16 sec (from top-left to bottom-right).

The typical flaming and burning behavior are shown in **Figure 3.** The start of dropping is 0.04 sec before the second image in the figure. The heating device contacted with the sample immediately after dropping to promote a quick ignition. It is found that the "weak" igniter flame enveloped the sample to promote the gasification of PMMA to induce to form the subsequent luminous PMMA flame within less than 0.5 sec after the ignition. The heating wire was retracted 0.6 sec or less from the onset of capsule dropping. During the PMMA burning period, enormous luminous spots are ejected from the flame, implying that the soot bursting as found in sooty ethylene flame in microgravity [5)]. Although not shown in figure, several frames before the extinction, strong luminous zone suddenly appeared at the top portion of the sample. This might be evidence that the drop approaches to the end hence the gravity start to play a role. In other words, free-fall is successfully made and the microgravity condition was maintained for most of the measured timing in this experiment.

As noted in sequential images above, it is quite obvious that entire burning procedure does not exhibit the "steady", rather, strongly fluctuated, especially after the PMMA flaming. Soot bursting has been frequently yet randomly identified and the flame shape tends to deform although the averaged flame image is nearly spherical. Interestingly soot bursting is less pronounced in the later stage of the drop. This might be attributed to the fact that the sample becomes small enough to reach uniformity (close to the ideal condition). As identified, even fluctuation is observed randomly, averaged flame shape is close to the spherical. It is suggested that bursting time scale is too short to vary the entire thermal states around the flame to attain quasi-steady state. In this sense, it is highly possible to adopt classical d-square law to characterize the burning behavior of PMMA sphere. In the next section, we shall investigate the size of the sample in time to check the feasibility of the d-square law in this system.

3.2. Measured Burning Rate Constant

According to the droplet burning theory, well-known "d-square law (eq.1)" should be adopted when 1-D burning structure is fulfilled.

$$d(t)^2 = d_0{}^2 - Kt \tag{1}$$

Here, t is the elapsed time [s], d(t) stands for the diameter of the burning specimen at specific time of t [m], and K is so called burning rate constant [m^2/s], describing the characteristic burning speed of the specimen. Burning rate constant shall be measured from observed d-square data in time. In **Figure 4 (a)**, d-square value is plotted in time. Random fluctuation in d-square value is found in early stage of the burning, while, it reduces linearly in time in later stage. Noted that the first stage stands for "Stage I" and the second stage stands for "Stage II", respectively. The boundary of Stages I and II shall be determined by the sharp variation in moving average.

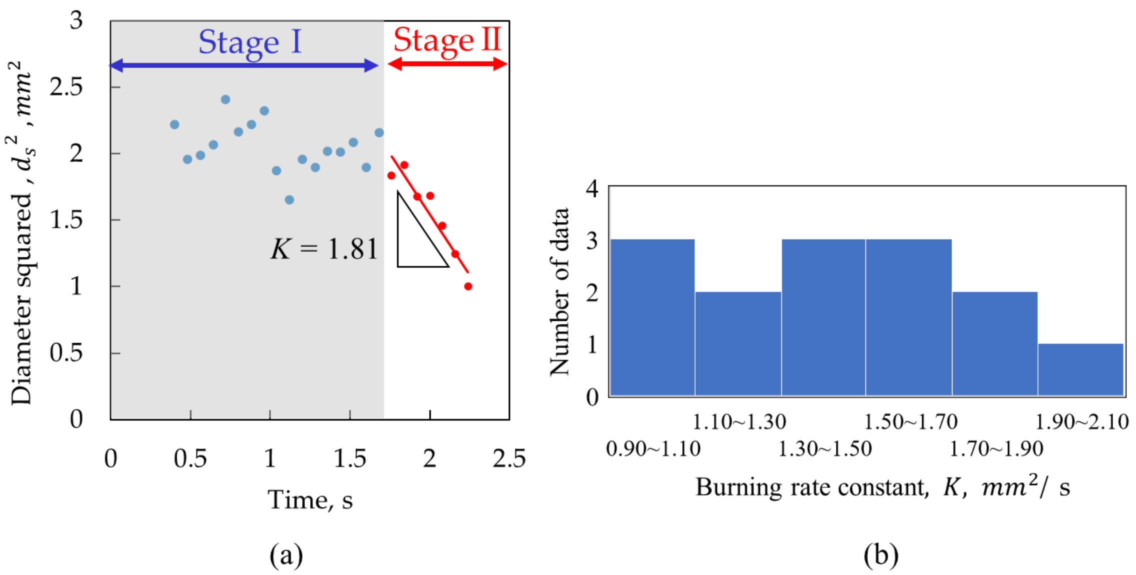

Figure 4. d-square law in this study, (a) Changes of the diameter squared in time (K = 1.81 mm^2/s), (b) Distribution of K obtained from 14 runs in microgravity

The cause of fluctuation in Stage-I would be due to competing effect of reduction of size by burning and the volume expansion with "void" inside the burning polymer where molten matter is presented. However, the former reason (size reduction of burning) is relatively stable process without any abrupt effect, therefore, it would not be the main cause of the large fluctuation as indicated. In contrast, the latter cause (volume expansion) is more responsible to cause the large fluctuation as observed. If so, the Stage-II followed by the frequent void appearance shall be affected by the void formation process at Stage-I. To end, the burning rate constant, K obtained under the same conditions differ greatly as shown in **Figure 4 (b)**, where the probability distribution of the burning rate constant, for example, $K = 1.10$ mm^2/s and $K = 1.81$ mm^2/s.

When looked closely the burning behavior of those two cases such as $K = 1.10$ mm^2/s and $K = 1.81$ mm^2/s, the typical differences between two cases are found. That behavior observed in this study and of that reported by NIST [1,2] are shown in **Figure 5**.

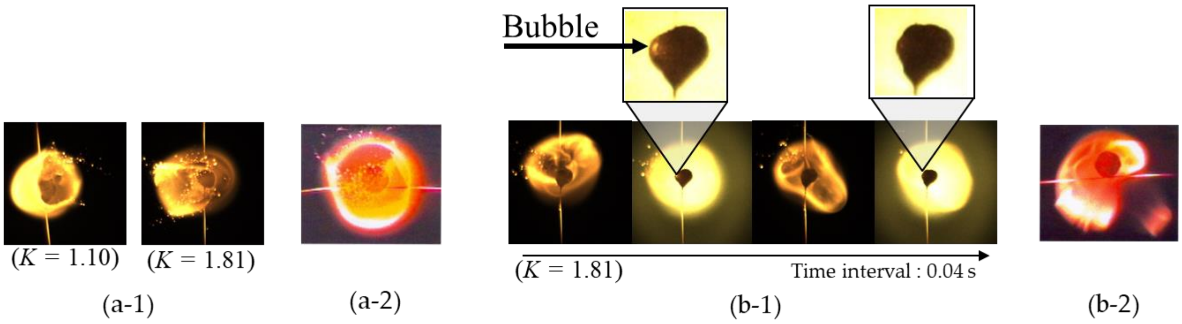

Figure 5. Burning PMMA sphere and dynamic behavior in microgravity. (a-1) Captured in Stage I ($K = 1.10$ mm^2/s), ($K = 1.81$ mm^2/s), respectively in this study, (a-2) Break up of a soot shell reported by NIST [1,2], (b-1) Captured in Stage II ($K = 1.81$ mm^2/s) in this study, (b-2) Bubble bursting reported by NIST [1,2]

Typical examples of burning behavior captured in Stage-I and Stage-II, respectively in this study seem to be same as that reported by NIST [1,2]. In Stage I, strong luminous part is seen around or in some parts of flame, and the shape of the flame is distorted from that of a sphere (**Figure 5 (a-1)**). This behavior was confirmed every time in all cases (14 runs in microgravity). Again, it seems to have occurred due to soot bursting (break-up of a soot shell) located between the luminous flame zone and surface of the sample [6,7]. In Stage II, on the contrary, the bubble nucleation and bursting at the sample surface were often observed (**Figure 5 (b-1)**). The flame observed by NIST **(b-2)** has luminous flame protrusion due to ejection of molten matter associated with bubble bursting, while that observed in this study **(b-1)** does not have luminous flame protrusion. However, burning specimen can be seen from the LED backlight images, and its shape changed from second frame to fourth frame. It would be the evidence the occurrence of the bubble burst, as a result, the flame shape was disturbed substantially. Noted that this behavior tends to be appeared in most of cases identified the larger K. Bubble nucleation (not sure if it bursts) randomly occurs during combustion because it is caused by the gasification inside the molten matter. Though it is difficult to confirm full story from only captured backlight (2-D) images, those types of dynamic behavior (such as breaking up of a soot shell, bubble nucleation and bursting) occurred during not only Stage I, but also Stage II (duration to characterize the burning rate constant). At least one type of those behavior was observed in every experiments. It is important to identify through the present 14 runs that the cause for the difference between K obtained under the same conditions is presumed to be dynamic behavior.

4. Remarks

The microgravity combustion experiments of PMMA sphere were conducted to investigate the effect of dynamic behavior and investigate it effects on burning character. Abrupt and complex dynamic behavior was observed every time in experiments under the same conditions. It occurred randomly during combustion, and burning rate constant is different at each experiment. The investigation indicates that dynamic behavior during combustion effect on burning character obtained from d-square law.

Acknowledgement

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