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球形固体パラフィン燃料の気化速度定数取得に向けた予備実験

Preliminary investigation for measurement of gasification-rate constant of spherical solid paraffin fuel

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Abstract: Hybrid rocket engines using paraffin-based fuel are characterized by the formation of a melting layer on the fuel surface, from which small fragments are entrained into the oxidizer flow and undergo droplet combustion. This process affects both regression rate and overall combustion efficiency, making the study of fuel sphere combustion essential for understanding hybrid rocket engine performance. In this work, sub-millimeter paraffin fuel spheres (FT0070) were prepared by injecting molten paraffin wax and suspending them on silicon carbide (SiC) fibers. Combustion was initiated using an electrically heated iron–chromium alloy wire, with the process recorded at 1000 frames per second using a high-speed camera (iN8-S2). Two backlighting methods for measuring the fuel sphere diameter and the gasification-rate constant were evaluated: a surface light source, which provided clear visualization of melting process and flame development but having interference with fuel sphere boundary detection, and point light source, which reduced background noise and enabled clearer tracking of the fuel sphere outline. Image analysis was conducted using MATLAB program that applied binarization and circular fitting techniques to determine fuel sphere diameters. Occasional measurement errors were observed due to the limitations in the circular fitting algorithm, suggesting that optimization of the MATLAB analysis program is still necessary to achieve higher accuracy and consistency in fuel sphere size measurement.

Keywords: **Hybrid rocket, Droplet combustion, Paraffin fuel, Normal gravity, Gasification-rate constant**

1. Background

Hybrid rocket engines utilizing paraffin-based fuel exhibit unique combustion characteristics due to the formation of a melting fuel layer on the grain surface. During operation, the oxidizer flow over this melting layer induces entrainment, whereby small portions of the fuel are detached from the molten surface and suspended within the combustion chamber. These detached fuel fragments can undergo droplet combustion, which influences both the fuel regression rate and overall combustion efficiency.

Understanding the combustion behavior of paraffin-based fuel in its droplet form is therefore essential for elucidating the physical and chemical processes occurring inside a hybrid rocket engine. The droplet combustion process can be described by the d^2-law, which states that the square of the droplet diameter decreases linearly with time:

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

where d is the droplet diameter at time (t), d_0 is the initial droplet diameter, and K is the vaporization rate constant. If paraffin-based solid fuels are used, not only vaporization but also liquid phase pyrolysis will contribute to the gasification of the fuel sphere. Hereinafter, we refer to K as the gasification-rate constant for spherical solid paraffin fuels.

This study focuses on experimentally investigating the combustion characteristics of paraffin-based fuel droplets under ambient pressure and normal gravity. This study acts as preliminary investigation which aims to determine the gasification-rate constant K and assess the applicability of the d^2-law for paraffin fuel sphere combustion

2. Methods

2.1. *Paraffin-based Fuel Sphere Generation and Suspension*

Sub-millimeter paraffin-based fuel spheres were prepared by injecting molten paraffin wax (FT0070) through a fine glass tube while maintaining the fuel temperature above its melting point to ensure smooth formation. The solid spheres were supported on silicon carbide (SiC) fibers arranged in a three-fiber configuration. Two parallel fibers were positioned 10 mm apart, and a third fiber was placed perpendicular to each of the parallel fibers to better hold the fuel sphere. This configuration allowed the droplet to remain suspended with minimal heat conduction losses and reduced optical interference during recording.

2.2. *Ignition*

Ignition of the fuel spheres was achieved using an iron–chromium alloy wire heated electrically with a 24 V, 4.4 A supply. The ignition system setup is shown in Figure 1. The heating element was placed close to the suspended fuel sphere and activated at the start of the recording sequence to allow both the melting of the solid fuel and subsequent combustion process to be fully observed. This setup ensured that the entire combustion event was captured from initiation to extinction.

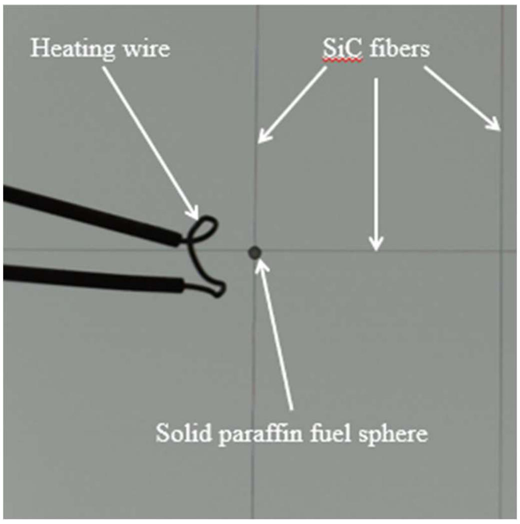


Figure 1. Setup of ignition system with suspended solid fuel sphere on SiC fibers

2.3. *Optical Recording*

The combustion process was recorded using a high-speed camera operating at 1000 frames per second, enabling the capture of rapid changes in droplet size during burning. Illumination was provided by the built-in LED light of a smartphone, positioned behind the suspended droplet to act as a backlight. This setup enhanced the contrast between the droplet and the background, allowing for clearer identification of the droplet boundary in each frame. Recording began simultaneously with the activation of the electric heating wire, ensuring that the ignition and subsequent combustion stages were fully documented.

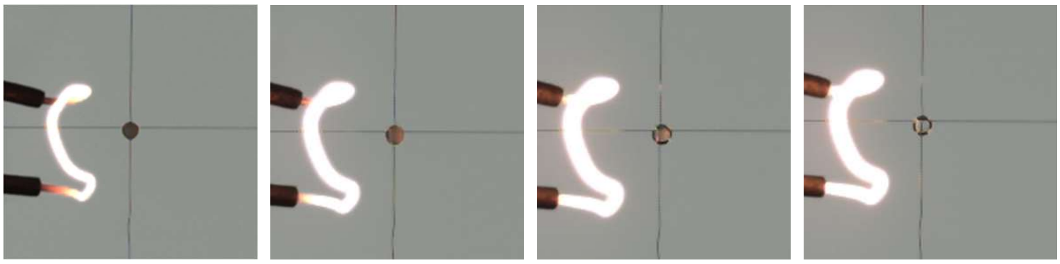
2.4. *Image Processing and Diameter Measurement*

Image analysis was carried out using a MATLAB program developed by Iwai[1)]. Each recorded frame was first subjected to a binarization process to isolate the droplet from the background. The program then approximated the droplet boundary by fitting a circle to the detected contour. The diameter of this fitted circle was converted from pixels to physical units using the known spacing of the SiC fibers (10 mm) as a reference scale. To verify measurement accuracy, the program overlaid the fitted circle on the original image, enabling visual confirmation that the calculated diameter matched the actual droplet outline.

3. Results

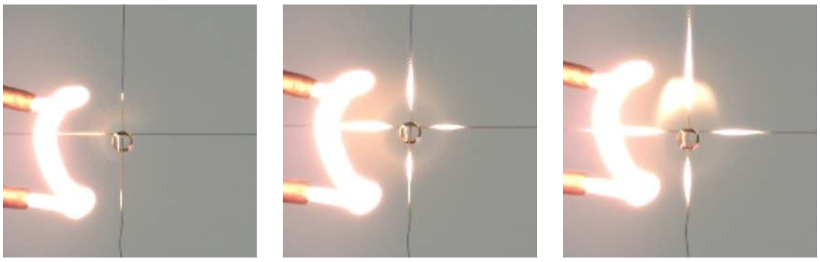
The use of different backlight configurations provided complementary insights into the combustion process. As shown in Figure 2 and 3, with the surface light source, melting process and flame development was clearly visible, especially enabling observation of the envelope flame, which evolved into a characteristic teardrop shape. This phenomenon, caused by natural convection, is thought to enhance oxidizer supply and may have contributed to an increased gasification-rate under the tested conditions. However, the interference from the glowing ignition wire and supporting fibers made the fuel sphere outline difficult to track with precision.

In contrast, Figure 4 shows the point light source setup, combined with shorter camera exposure times, successfully reduced background noise and provided clearer identification of the fuel sphere boundary. This improvement facilitated diameter tracking throughout combustion. However, the MATLAB analysis revealed occasional errors which manifested as sudden jumps or drops in the measured diameter. Visual confirmation indicated that these deviations were due to limitations in the circular fitting algorithm. These findings suggest that optimization of the MATLAB analysis program is still necessary to achieve higher accuracy and consistency in droplet size measurement.



(a) (b) (c) (d)

Figure 2. Fuel sphere melting process under normal gravity and exposure time of 705 μs. (a) 0.410 sec into recording, (b) 0.5 sec into recording, (c) 0.59 sec into recording, (d) 0.68 sec into recording.



(a) (b) (c)

Figure 3. Flame development process under normal gravity and exposure time of 705 μs. (a) 1.232 sec into recording, (b) 1.24 sec into recording, (c) 1.26 sec into recording.

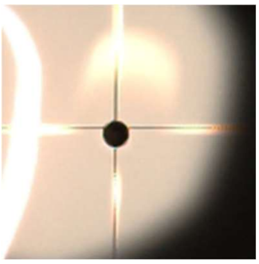


Figure 4. Maximum flame size and fuel sphere appearance in point light source backlight recording with exposure time of 50 μs.

Conclusion

This study experimentally investigated the combustion of paraffin-based fuel sphere under normal gravity and ambient pressure. The key findings are as follows:

1. The surface light source backlight allowed clear observation of flame development, including the transition into a teardrop-shaped envelope flame caused by natural convection.
2. The point light source backlight minimized background noise and improved fuel sphere boundary detection.
3. Occasional measurement errors were attributed to limitations in the MATLAB fitting algorithm, indicating the need for further optimization.
4. Additional experiments and refined analysis methods are necessary to accurately determine the gasification-rate constant K and improve statistical reliability.

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