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# 単一アンモニア液滴の着火方法調査と微小重力場・高圧雰囲気における燃焼速度定数計測

# Investigation of ignition methods of single ammonia droplets and measurement of burning-rate constant at high pressure in microgravity

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### 1. Introduction

Spray combustion is widely used in liquid-fueled combustors. However, the detailed mechanism has not been clarified completely because various physical and chemical processes proceed simultaneously. In order to improve understanding of its mechanism, many studies on combustion of a single droplet, which is a component of spray, have been conducted from a fundamental viewpoint. In addition, in recent years when the movement of carbon neutral is becoming popular, many studies on combustion using carbon neutral fuels are actively conducted. Ammonia is one of them. Another merit of using liquid ammonia as a fuel is that the cost of change of the existing supply system can be minimized. Okafor et al. [1)] succeeded in stabilizing ammonia spray combustion using a high-temperature swirling air flow. Since ammonia is in gaseous state at normal temperature and atmospheric pressure, however, it is difficult to handle it as a liquid. So, researches using single ammonia droplets have rarely been conducted. Matsuura et al. [2)] succeeded in generating single ammonia droplets and measuring vaporization-rate constant as the first step. However, it is known that ammonia is difficult to ignite because the heating value is much lower than that of hydrocarbon fuels, and the latent heat of vaporization is much greater, and so on.

At the second step, this study investigated methods of igniting single ammonia droplets at a pressure higher than saturation pressure of ammonia at room temperature. Therefore, the burning-rate constant, which is an important index for investigating the combustion characteristics of an ammonia droplet, was measured at high pressure in a microgravity.

## 2. Experimental apparatus and procedure

This study used high-pressure condition to observe burning of ammonia droplets. Liquid ammonia was first supplied to a vacuumed high-pressure syringe, which is a part of the ammonia-droplet-generation system. Then the liquid ammonia supply path was pressurized by $N_2$, so that ammonia vapor generated in the syringe was fully liquefied and thus the syringe was filled only with liquid ammonia. The syringe with liquid ammonia was installed in the droplet-generation system, which was inserted into the pressure vessel. The pressure vessel was pressurized at 1.5 MPa using mixed air ($N_2$ 79%, $O_2$ 21%). **Figure 1** shows the ammonia droplet generation system, which is equipped with a three-axis traverse stage that moves the glass tube and pushes out the syringe with liquid ammonia, a fiber base with crossed SiC fibers, a self-designed syringe, and a solenoid valve. An ammonia droplet was generated through the fine glass tube by supplying liquid ammonia from the stepping-motor-driven syringe after the solenoid valve was opened. After an ammonia droplet was generated, it was ignited by the igniter in microgravity. A hot wire ignition was used for the ignition method. For measuring burning-rate constant, it is better to remove the igniter from the field of view. Therefore, we made a device to remove the igniter using a stepping motor, as shown in **Fig. 1**. To achieve the purpose of this study, two type shapes of igniter were used for ignition trial, as shown in **Fig. 2**. The main change was the shape of hot-wire. First, as shown in **Fig. 2(a)**, the hot-wire was looped to surround the droplet to ignite easier, which is named “Ver. 1”. Second, we employed another type of igniter in **Fig. 2(b)**, named “Ver. 2”, which is moved away from the vicinity of the droplet. As shown in **Fig. 2(b)**, the lower half of the droplet is surrounded by the hot-wire when viewed from the top, and in **Fig. 2(c)**, the droplet is sandwiched from both sides when viewed from the side. The energization time was set to 200ms for both of types. The microgravity experiments were conducted at a drop experiment facility of Yamaguchi University. The falling distance is 4.5 m and the microgravity duration is 0.9 s.

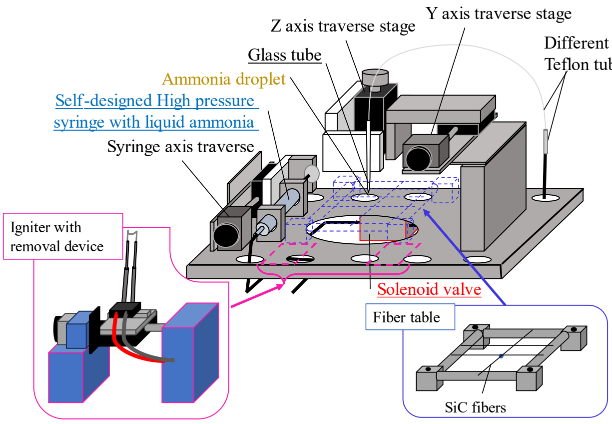


**Figure 1.** Ammonia droplet generation system with an igniter removal devise.

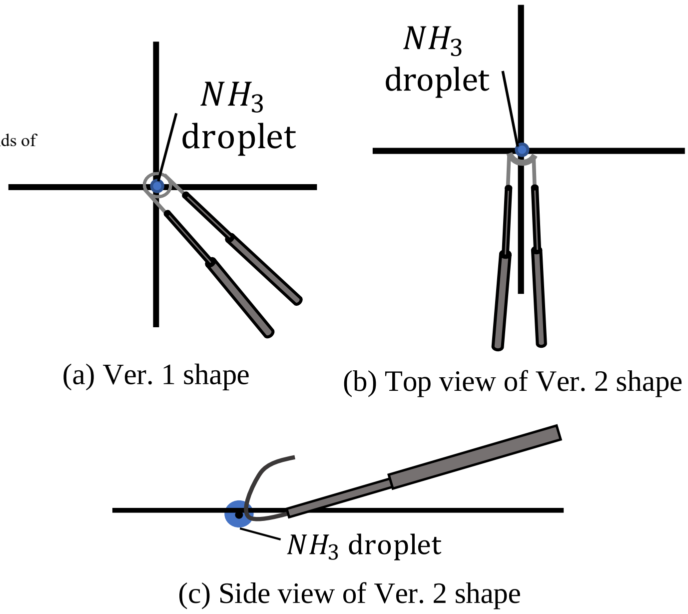


**Figure 2.** Shape types of hot-wire of igniters

## 3. Results and discussion

3.1 Ignition trial of single ammonia droplets by changing oxygen concentration in normal gravity

Ammonia has the characteristic of being difficult to burn. Moreover, it is much more difficult to ignite liquid ammonia than gaseous ammonia due to its latent heat of vaporization. Matsuura et al. carried out ignition trials of ammonia droplets in air in normal gravity. They reported that the ammonia droplets did not ignite, and only the red heat of the hot-wire created an ammonia vapor cloud[3)]. Therefore, aiming to promote ignition by lowering the ignition temperature and raising the flame temperature, an ignition trial was conducted by increasing the ambient oxygen concentration. The oxygen concentration was changed to 25%, 30%, 35%, and 40%, where mixed air and pure oxygen were mixed. A fan was installed in the pressure vessel so that the oxygen concentration was uniform. As results, the ignition of ammonia droplets was not realized at oxygen concentrations of 25% and 30%. At 35% oxygen concentration, ammonia droplets were sometimes ignited. At 40%, conditions were met for ignition in normal gravity. **Figure 3** shows sequential images of ammonia droplet flame at 40% oxygen concentration with the initial droplet diameter of 1.1mm using the looped type hot-wire shown in **Fig. 2(a)**. Here, we define 0 s as the start of camera shooting. After the flame formed, the ammonia droplets continued to burn, and after a certain period of time, the droplets flew and fell.

3.2 Ignition trial in microgravity.

Since the effect of gravity on spray droplets is negligible, investigations in microgravity are necessary for practical application. In addition, the natural convection becomes negligible in microgravity, so the ignition probably becomes easier. Therefore, we tried to ignite ammonia droplets in microgravity. We used mixed air ($N_2$ 79%, $O_2$ 21%) as the ambient gas. **Figure 4** shows sequential images of the flame of ammonia droplet using Ver. 1 shape in **Fig. 2(a)** with the initial droplet diameter of 1.1 mm. **Figure 5** shows them using a device to remove the igniter shown in Fig. 1 and Ver. 2 shape in **Fig. 2(b)** with the initial droplet diameter of 1.1 mm. **Figures 4** and **5** clearly show that the ignition of an ammonia droplet was realized in high-pressure air atmosphere in microgravity. Here, we defined 0 s as the fall start. As shown in **Fig. 4,** a flame was observed immediately after ignition, and the intensity of the flame brightness became weaker in the latter stage of combustion. The red heat of SiC fibers suggests the presence of the flame. As shown in **Fig. 5**, from early to middle stage of combustion, the tendency is similar to **Fig. 4**, however, the flame rapidly contracted in the latter stage of combustion, and the droplets finally bursted. The phenomenon that the droplet expands once and then shrinks or bursts was observed several times. We will continue to figure out this phenomenon.

3.3 Measurement of burning-rate constant in microgravity

We confirmed the appearance of the ammonia droplet flame in microgravity and therefore measured the burning-rate constant of the ammonia droplet flame. Burning-rate constant is the important index for investigating the combustion characteristics of droplet flames. The $d^2$- law, in which the squared value of the droplet diameter decreases linearly, is expressed as Eq. (1), where $K_b$ is burning-rate constant.

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

**Figure 6** shows the variation of squared droplet diameter over time for a single ammonia droplet of **Fig. 5**. According to **Fig. 6**, the burning-rate constant of ammonia droplet has two steps: the first step, a constant burning-rate constant is shown from the beginning of combustion to the middle of combustion; and the second step, $K_b$ becomes gentle about 0.1 s before the droplet diameter becomes unmeasurable. **Table 1** shows the results of measurement, such as the initial droplet diameter $d_0$, the first-step burning-rate constant $K_{bF}$, the second-step burning-rate constant $K_{bS}$. The first step, $K_{bF}$ is 0.89~0.98 mm²/s and the second step, $K_{bS}$ is 0.44~0.49 mm²/s. We will investigate the details of this phenomenon in the future.

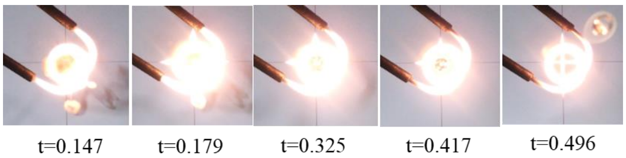


**Figure 3.** Sequential images of ammonia droplet flame in normal gravity at 40% oxygen concentration


**Figure 4.** Sequential images of ammonia droplet flame with Ver. 1 shape hot-wire in air in microgravity

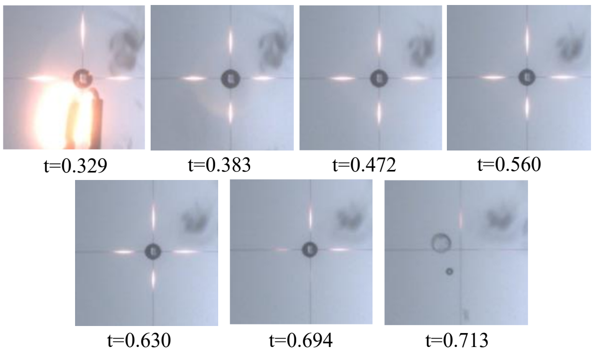


**Figure 5.** Sequential images of ammonia droplet flame with Ver. 2 shape hot-wire and igniter removal device

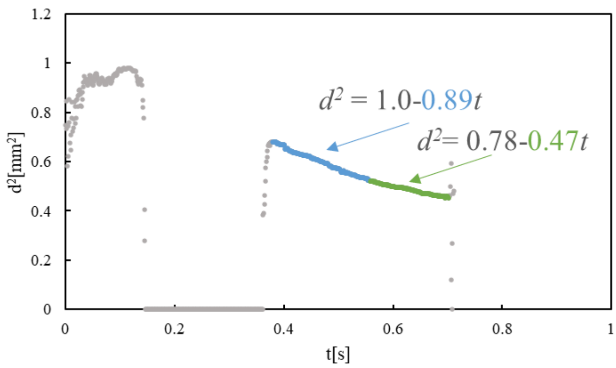


**Figure 6.** The variation of squared droplet diameter over time in air in microgravity

**Table 1.** Measured burning-rate constant in microgravity $K_b$ and various parameters

| | Initial droplet diameter [mm] | Ambient pressure [MPa] | Ambient tempeature [K] | $K_{bF}$ [mm²/s] | $K_{bS}$ [mm²/s] |
|---|---|---|---|---|---|
| Droplet 1 | 1.3 | | 299 | 0.97 | 0.49 |
| Droplet 2 | 1.1 | 1.5 | 300 | 0.89 | 0.47 |
| Droplet 3 | 0.99 | | 301 | 0.98 | 0.44 |

## 4. Conclusions

This study investigated methods of igniting single ammonia droplets at a pressure higher than saturation pressure of ammonia at room temperature and the burning-rate constant was measured at high pressure in microgravity. The conclusions of this study are as follows.

1. Single ammonia droplets were ignited in an air/oxygen mixture with an oxygen concentration of 40% at high pressure in normal gravity.

2. Single ammonia droplets were ignited in a mixed air atmosphere at high pressure in microgravity.

3. The burning-rate constant of a single ammonia droplet in microgravity varied in two steps: the first step was 0.89~0.98 $mm^2/s$ and the second step were 0.44~0.49 $mm^2/s$.


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## References


1) E.C. Okafor, H. Yamashita, A. Hayakawa, K. D. Kunkuma A. Somarathne, T. Kudo, T. Tsujimura, M. Uchida, S. Ito, H. Kobayashi: Fuel, 287, 2021, 119433.
2) Y. Matsuura, Y. Hara, M. Mikami, Measurement of vaporization rate of single ammonia droplets in room-temperature high-pressure air in microgravity, JASMAC-34, 2022.
3) Y. Matsuura, Y. Hara, Y. Chikami, T. Seo, M. Mikami, Realization of single ammonia droplet generation and combustion attempt at high pressure, The Japan Society of Mechanical Engineers Chugoku-Shikoku Student Association 52nd Student Member Graduation Research Presentation Meeting (in Japanese), 2022.