JASMAC
Conference of the Japan Society of Microgravity Application

OR4-4

微小重力場における高温雰囲気中での燃料液滴列の冷炎燃え広がり

Cool flame spread of a fuel droplet array in a high-temperature atmosphere in microgravity

藤枝佑毅 [1], 菅沼祐介 [2], 齊藤允教 [3], 田辺光昭 [3], 野村浩司 [2]
Yuki Fujieda[1], Yusuke Suganuma[2], Masanori Saito[3], Mitsuaki Tanabe[3] and Hiroshi Nomura[2]
[1] 日本大学大学院生産工学研究科，Graduate school Industrial Technology, Nihon University
[2] 日本大学生産工学部，College of Industrial Technology, Nihon University
[3] 日本大学理工学部，College of Science and Technology, Nihon University

1. Introduction

Hydrocarbon fuels used in diesel engines and gas turbines may undergo a two-stage combustion process in high-temperature, high-pressure environments in which a low-temperature oxidation reaction, the cool flame, is followed by a high-temperature oxidation reaction, the hot flame. This cool flame reaction is known to affect the subsequent hot flame. Therefore, it is important to clarify the combustion characteristics of the cool flame to understand the details of combustion phenomena.

Tanabe et al. confirmed the occurrence of a cool flame in a single droplet experiment[1)]. Moriue et al. studied the interference effect of the cool flame reaction between two droplets[2)]. However, no experiment has been performed to observe the spread of a cool flame by forced ignition of a droplet array. In this study, a cool flame spreading experiment was conducted by inserting a fuel droplet array into a high-temperature atmosphere in microgravity and forcibly igniting the droplets. In this report, we present the results obtained from the cool flame spreading experiments.

2. Experimental apparatus and conditions

2.1. Experimental apparatus

The experimental apparatus used in this study consists of a cool flame igniter, a combustion chamber, a droplet array holder, a droplet generator, a droplet array mover, a temperature controller, an optical system, a wireless LAN interface, and a power supply system. The cool flame igniter consists of an ignition wire and an ignition circuit with automatic power adjustment. 0.1 mm diameter nickel wire was used for the ignition wire. In this study, the circuit is based on the principle of a hot wire anemometer, and consists of a Wheatstone bridge, a differential amplifier, and a transistor to forcibly ignite a fuel droplet array and generate a cool flame only. This circuit allows the temperature of the ignition line to be adjusted to an arbitrary value by adjusting the variable resistor in the bridge. As a mechanism, unbalanced voltage from the Wheatstone bridge is input to the differential amplifier. The current is then amplified by a transistor to produce the current required for heating. A feedback circuit is incorporated to set the unbalanced voltage from the bridge to 0 V by means of a differential amplifier, which instantly makes the heating wire red hot and maintains it at a constant temperature. When a cool flame is generated, the differential amplifier in the ignition circuit lowers its output to return to the set value as the ignition wire is heated by the cool flame, which causes a voltage drop. Therefore, the occurrence of a cool flame can be confirmed by the voltage drop in the circuit.

The droplet array holder consisted of SUS tubes with diameters of 1.0 and 1.6 mm and was fixed by silver brazing at the intersection points. The plates for fixing the support frame were made of stainless steel to prevent the temperature drop in the combustion chamber and to withstand the shock during the drop experiment. The droplets are held in place by SiC fibers stretched in an X-shape with glass beads attached at the intersections.

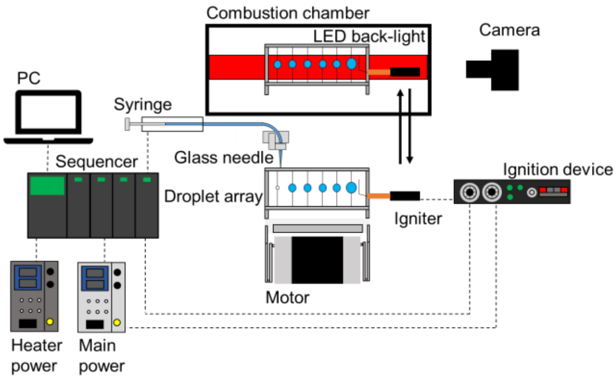

Figure 1. Experimental apparatus.

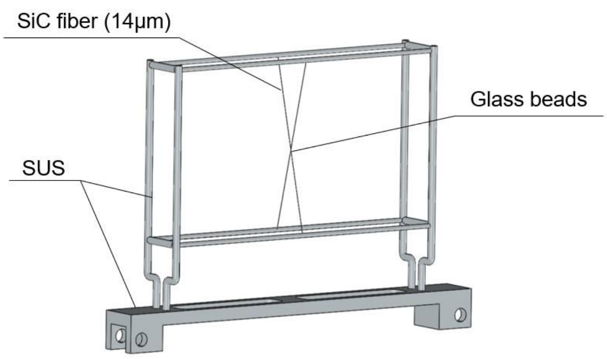

Figure 2. Droplet array holder.

2.2. Experimental conditions

The ambient temperature in the combustion chamber was 523 K. The droplet spacing S was set to 2 mm and 4 mm. 6 droplets were suspended at S = 2 mm and 4 droplets at S = 4 mm. The ignition line temperature was about 1015 K. The ignition device was activated 1.0 second after the droplet array holder had fully risen to the measurement position in the combustion chamber. n-decane was used as the fuel to allow comparison with the experimental results of other researchers. The initial droplet diameter d_0 for the first droplet as the ignition source was 1.0 mm, and d_0 for the second through sixth droplets was 0.75 mm. The experiment was conducted at Cosmotorre, a 50-meter class microgravity experimental facility. This experimental facility can produce a microgravity time of approximately 2.5 seconds. The voltage waveforms of the ignition system were recorded by a sequencer to confirm the generation of the cool flame. The droplet diameters were measured using the backlit method, in which the droplet is backlit from behind, and the outline of the droplet was photographed by a CMOS camera. The droplet diameter was analyzed from the photographed droplet images using a self-made program.

Table 1. Experimental conditions.

Fuel		n-decane	
Atmosphere pressure P_a (MPa)		0.10	
Gravity		normal gravity	microgravity
Droplet spacing S (mm)		2.0	2.0, 4.0
Initial droplet diameter d_0 (mm)	**1st**	1.0	
	2nd~6th	0.75	
Distance between droplet center and igniter (mm)		1.0	
Igniter temperature T_{ig} (K)		1015	
Atmosphere temperature in combustion chamber T_a (K)		523	
Ignition device operating time $t_{igon/off}$ (s)		1.0	
Ignition device operation waiting time t_{igw} (s)		1.0	

3. Result and Discussion

Experiments were conducted at an ambient temperature of 523 K in a combustion chamber with a waiting time t_{igw} of 1.0 seconds for ignition activation. Figure 3 shows the image of a droplet taken by the backlit method. From the obtained droplet images, droplet diameters were analyzed using a self-made program to calculate the droplet diameter history. The diameter history of a droplet in microgravity is shown in Figure 4. The first droplet, which is the ignition source, and the sixth droplet in normal gravity, which was difficult to measure, were excluded from the results. The droplet diameter histories in microgravity at an ambient temperature of 523 K and a droplet spacing of 2 mm show that the slope of the graph for the first droplet changes significantly at about 1.37 seconds. This indicates that the cool flame ignition occurred at about 0.37 seconds after the ignition device was activated. In addition, the large change in the slope of the graph after the first droplet suggests that the cool flame spread to the sixth droplet. The graph also shows a significant change in slope from the first to the fourth droplet at a droplet diameter of 4 mm, which indicates the spread of the cool flame.

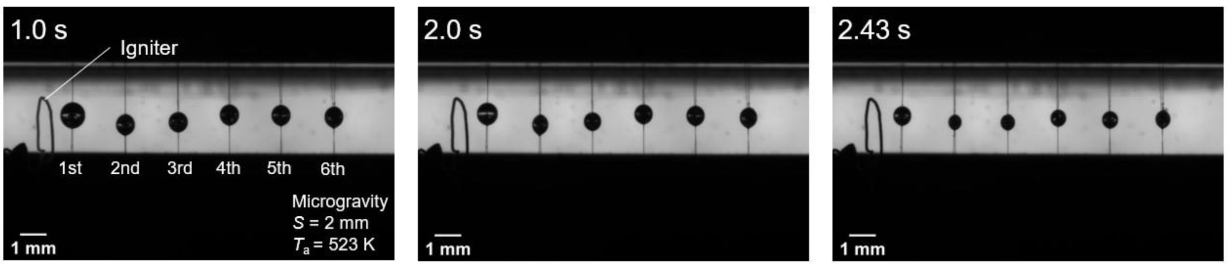

Figure 3. Backlit image.

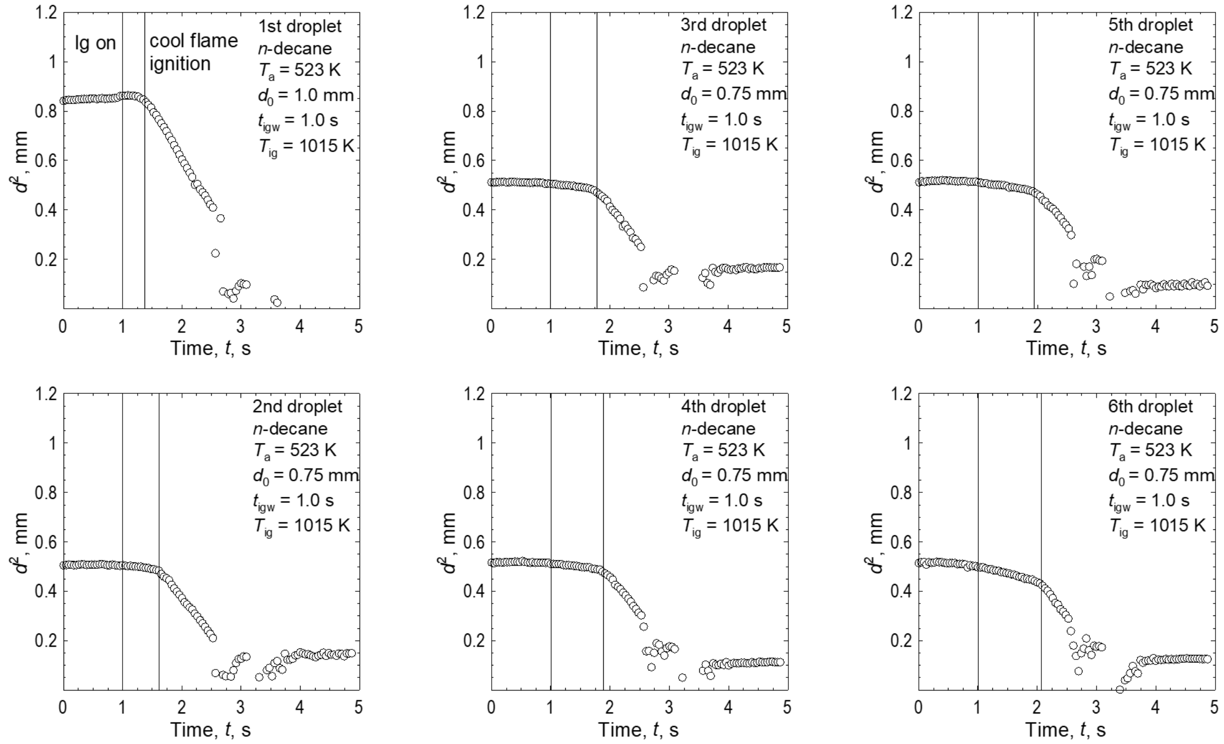

Figure 4. Droplet diameter history.

Figure 5 shows the relationship between the cool flame ignition time and droplet position obtained from the droplet diameter history. The cool flame spread speed, $V_{cf,}$ was calculated by approximating the plot with a straight line using the least-squares method and calculating the slope. Comparing the results of normal gravity and microgravity with a droplet spacing of 2 mm, the cool flame spread speed was about 15.6 mm/s in normal gravity and about 17.9 mm/s in microgravity, which was faster than that in normal gravity. In the case of normal gravity, the fuel vapor evaporated from the droplet is affected by gravity and flows down the droplet. On the other hand, in microgravity, sufficient combustible mixture can stay around the droplet, which promotes the flame spreading, thus accelerating the flame spread speed.

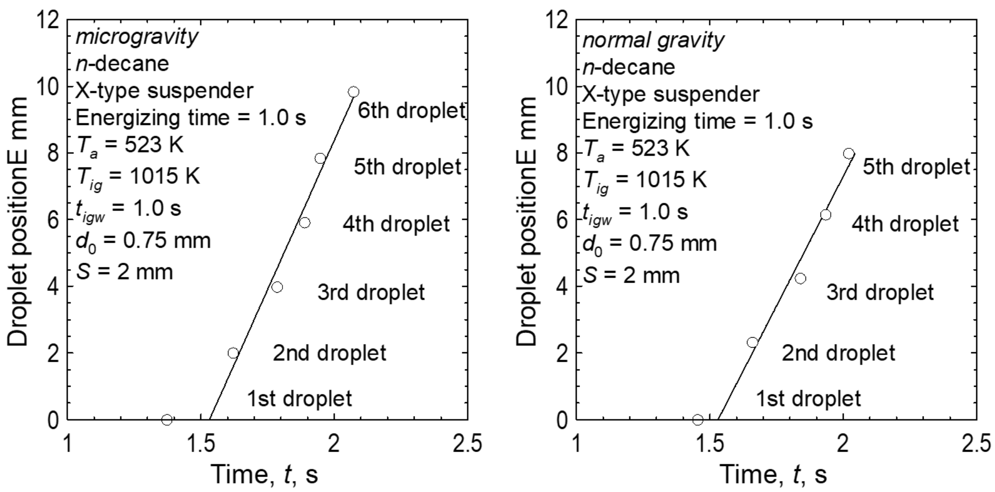

Figure 5. Relationship between cool flame ignition time and droplet position (S = 2 mm).

Figure 6 shows the relationship between cool flame ignition time and droplet position obtained from the droplet diameter history at a droplet spacing of S = 4 mm. Figure 7 shows the relationship between the nondimensional droplet spacing and the normalized cool flame spread speed in microgravity and normal gravity. The cool flame spread speed at S = 4 mm droplet spacing was 20.8 mm/s, indicating that the cool flame spread speed at S = 4 mm was faster than that at S = 2 mm in microgravity. In addition, Figure 7 suggests that the normalized cool flame spread speed tends to increase as the nondimensional droplet spacing increases. The above results suggest that the cool flame spread speed increases or decreases depending on the length of the droplet spacing in microgravity. This is thought to be due to interference effects caused by the coarseness and density of the droplets. Therefore, we plan to investigate the effect of droplet spacing on the spread speed of the cool flame by changing the value of S/d_0 in future experiments.

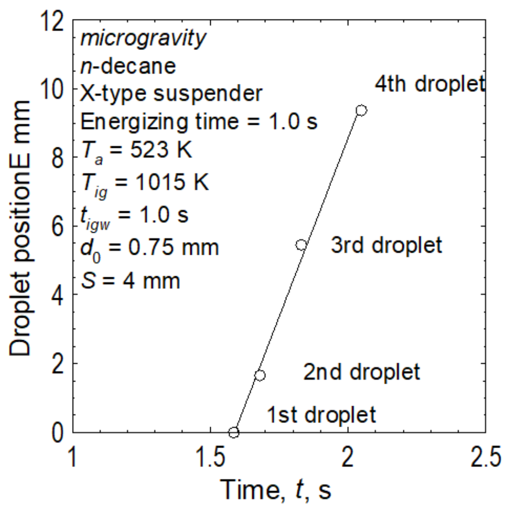

Figure 6. Relationship between cool flame ignition time and droplet position (S = 4 mm).

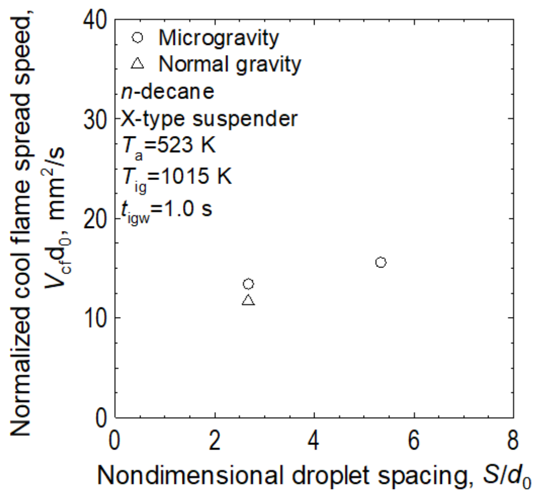

Figure 7. Relationship between nondimensional droplet spacing and normalized cool flame spread speed.

4. Conclusion

A forced ignition system was used to observe the cool flame spreading of fuel droplets in microgravity. The findings are summarized as follows.

- The droplet diameter history was measured by backlit images, and the cool flame ignition time was calculated by the diameter history.
- The cool flame spread speed was found to be faster in microgravity than in normal gravity.
- The cool flame spread speed was found to increase or decrease depending on the length of the droplet spacing in microgravity.

Acknowledgment

This study is supported by JSPS KAKENHI Grant #JP19K04843.

References

1) M.Tanabe, M. Kono, J. Sato, J. Koenig, C. Eigenbrod and H. J. Rath: Effects of natural convection on two stage ignition of an n-dodecane droplet. Symposium (International) on Combustion/The Combustion Institute, **25** (1994) 455
2) O. Moriue, Y. Nishiyama, Y. Yamaguchi, H. Hashimoto, E. Murase: Effects of droplet interaction on spontaneous ignition of an n-decane droplet pair. The Combustion Institute, **34** (2013) 1585