Observation of Spontaneous Ignition Behavior of a Fuel Droplet Pair by Interferometry

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As a fundamental study on the droplet-interaction effect in the fuel-spray ignition, spontaneous ignition of an \( n \)-decane droplet pair in hot air was experimentally studied in normal gravity and microgravity. Two suspended droplets initially at room temperature were brought into a hot furnace filled with air and ignited spontaneously. In the previous studies, cool-flame and hot-flame ignition delays were evaluated thorough thermocouple measurement, and their dependence on inter-droplet distance was discussed thorough the development of temperature and fuel-concentration distribution around a droplet pair. However, two-dimensional observation of cool-flame and hot-flame behavior was not possible with thermocouple measurement. In the present study, interferometry was applied in order to detect cool flame, which emits almost no visible light. Density field around a droplet pair was qualitatively observed with a high-speed camera, and the locations of cool-flame and hot-flame appearance were evaluated. Pressure was 0.3 MPa, and ambient temperature was between 560 and 680 K. The ambient conditions are in the range where two-stage ignition occurs. Initial droplet diameter was either 0.8 mm or 1 mm. In normal gravity, cool flame always appeared on the lower side of the droplet pair, and hot flame appeared on the upper side in most cases, which is obviously the effect of buoyancy. In microgravity, cool flame appeared on the outer side of the pair, and hot flame appeared on the inner side of the pair, which corresponds with the discussion in the previous studies.

Key Words: Fuel Droplet Pair, Spontaneous Ignition, Cool Flame, Interferometry, Microgravity

1. Introduction

Spontaneous ignition of an isolated fuel droplet in hot air has been studied by many researchers as a fundamental study for fuel-spray ignition.1-7) An isolated droplet is physically the simplest model of liquid fuel combustion. If the effect of buoyancy is negligible, the phenomenon is spherically symmetric, which simplifies the comparison between experiments and theoretical or numerical analysis. Through the past studies,4-6) the role of the low-temperature oxidation reactions in the isolated-droplet ignition was clarified. When the ambient conditions (pressure, \( P \), and ambient temperature, \( T_a \)) are in the range where the low-temperature oxidation reactions are active, cool flame is first induced by these reactions. Since the low-temperature oxidation reactions are inhibited as temperature increases, heat release by these reactions is suppressed after cool flame appeared. This leads to relatively low temperature of cool flame (typically lower than 1000 K). With a certain delay after cool-flame appearance, the high-temperature oxidation reactions are activated, which induce hot flame. Thus two-stage ignition occurs for most hydrocarbon fuels.

However, there exists interaction between droplets in a fuel spray, and its effect cannot be taken into account by an isolated droplet. In order to investigate the effect of the droplet interaction, spontaneous ignition of a fuel droplet pair was experimentally studied by the authors' group in microgravity.8,9) The studies were performed with special attention on cool flame. Temperature near the droplet pair was measured by thermocouples, and cool-flame ignition delay, \( \tau_{cf} \), and hot-flame ignition delay, \( \tau_{ig} \), were evaluated. Droplet interaction is supposed to have two counteracting effects. One is mutual cooling effect between droplets through duplicated heat sinks, and is supposed to be negative for ignition. The other is enhanced fuel supply through duplicated fuel sources and is supposed to be positive for ignition. As seen in Fig. 1, the experimental results9) showed that the mutual cooling effect was dominant before cool-flame appearance, while the effect of duplicated fuel sources was
dominant after cool-flame appearance. The results can be explained through the development of temperature and fuel concentration distribution. Smaller inter-droplet distance, \( l \), led to longer \( \tau_{cf} \) since the mutual cooling effect prevailed over the enhanced fuel supply for cool-flame appearance. Numerical analysis of premixed-gas ignition with detailed chemical kinetics tells that the low-temperature oxidation reactions are rather dominated by temperature than by fuel concentration. One should also note that \( \tau_{cf} \) includes the physical delay, i.e., the heat-up duration of the droplets. Second induction time, \( \tau_2 \), the duration between cool-flame appearance and hot-flame appearance decreased with decreasing \( l \). Since \( \tau_2 \) does not include the heat-up duration, it is supposed to depend mainly on the characteristics of the high-temperature oxidation reactions and the temperature in the reaction zone after cool-flame appearance. Shorter \( l \) is supposed to lead to higher cool-flame temperature, \( T_{cf} \), through higher fuel concentration in the reaction zone at cool-flame appearance. Numerical analysis of premixed-gas ignition tells that higher fuel concentration generally leads to higher \( T_{cf} \). However, the measurement in the previous studies was only by thermocouple, and the locations of cool-flame and hot-flame appearance were unclear. In the present study, two-dimensional observation of the spontaneous ignition of a fuel droplet pair in hot air was attempted. Michelson interferometer was applied in order to detect cool flame, which has almost no light emission. Density field around a droplet pair was qualitatively observed with a high-speed camera, and the locations of cool-flame and hot-flame appearance were evaluated. The experiments were performed first in normal gravity, and then in microgravity to exclude the effect of buoyancy.

2. Experimental Apparatus and Conditions

The apparatus is composed of a high-pressure chamber, optical recording system and controlling system. The high-pressure chamber contains an electric furnace, a droplet-pair suspender, a suspender driving device and a fuel supplying device. The droplet-pair suspender is shown in Fig. 2. Four SiC fibers with a diameter of 14 \( \mu \)m were fixed on two fiber holders, which were stainless steel pipes with a diameter of 1 mm. The distance between the two pipes was 30 mm. Two fuel droplets were generated on the intersections of SiC fibers at room temperature. Inter-droplet distance, \( l \), was defined as the distance between the two droplet centers. The fiber holders were supported on a base plate. Over the droplet pair was placed an electric furnace, which was thermally insulated. The inside temperature was automatically controlled to be a desired value. The droplet pair were inserted into the furnace through a slit and thus exposed from room temperature to high temperature rapidly. The whole travel time was 150 ms, while the transition time from room temperature to the high temperature was about 50 ms. Schematic of Michelson interferometer is shown in Fig.
3. He-Ne laser (wave length 633 nm) was used as a light source. The laser beam was expanded to 20 mm in diameter and led into the furnace through the windows. The direction of the laser beam was perpendicular to the plane containing four SiC fibers. Density distribution in the furnace was able to be qualitatively observed as fringes. The images were recorded by a high-speed camera with a frequency between 750 and 1200 fps. Fuel was $n$-decane, whose normal boiling point is 447 K. Pressure was at 0.3 MPa, and $T_a$ was between 560 and 680 K. The ambient conditions are in the range where two-stage ignition occurs. Initial droplet diameter, $d_0$, was either 0.8 mm or 1 mm. Inter-droplet distance, $l$, was fixed to 2 mm in the present study. The drop tower of College of Industrial Technology, Nihon University (microgravity duration: 0.7 s) was used as microgravity facility. The droplet pair was generated while the drop capsule was hanging. After the capsule release, it was inserted into the furnace.

3. Results and Discussion

3.1. Normal gravity experiments
Experiments were performed in normal gravity varying $T_a$ between 560 and 680 K. Typical images by interferometer are shown for $T_a=600$ K in Fig. 4. Vicinity of the droplet pair is trimmed. The origin of the time was defined as the

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Fig. 4. Images of an igniting droplet pair through interferometry (fuel: $n$-decane, $d_0=1.0$ mm, $P=0.3$ MPa, $T_a=600$ K, $l=2$ mm, in 1g, 1000 fps).

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Fig. 5. Locations of cool-flame appearance for different $T_a$ (fuel: $n$-decane, $d_0=1.0$ mm, $P=0.3$ MPa, $l=2$ mm, in 1g).

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Fig. 6. Locations of hot-flame appearance for different $T_a$ (fuel: $n$-decane, $d_0=1.0$ mm, $P=0.3$ MPa, $l=2$ mm, in 1g).
moment when the droplet pair started to be heated up, namely 50 ms before the end of insertion travel. Because of the buoyancy, fuel vapor from the droplets went downwards as seen in Fig. 4 (b). Then the direction of the convection changed (Fig. 4 (c)), which means that there was heat release on the lower side of the droplet pair. This is interpreted as cool-flame appearance. Cool flame shifted upwards and surrounded the droplet pair (Fig. 4 (d)). Finally, steep density distribution, i.e., temperature distribution appeared rapidly on the upper side of the droplet pair (Fig. 4 (e)), which means that there was large and rapid heat release. This is interpreted as hot-flame appearance.

Such experiments were performed for different \( T_a \). Figures 5 and 6 show the locations of cool-flame and hot-flame appearance, respectively, for different \( T_a \). Temperatures in the figures denote \( T_e \). Two filled circles show the positions of two droplets, and the vertical coordinate shows the distance from the middle point of two droplets in mm. For each \( T_a \), three experiments were performed, and some of the locations have wide area because of the data fluctuation. Another reason for the wide area especially for cool-flame appearance is that temperature gradient at cool-flame appearance is not so steep as that at hot-flame appearance, and therefore the location of cool-flame appearance can not be limited in a narrow area. Cool flame always appeared on the lower side of the droplet pair. This is obviously because relatively cold fuel vapor went downwards first because of its larger density. As \( T_a \) increased, the location of cool-flame appearance got closer to the droplet pair. This tendency had been observed for isolated droplets,\(^7\) and this is very likely because of shorter \( \tau_c \) with increasing \( T_e \). When \( \tau_c \) is short, cool flame appears before fuel vapor dissipates far from the droplet pair. Hot flame appeared on the upper side of the droplet pair except for \( T_a=580 \) K. This is because the direction of the convection changed after cool-flame appearance as seen in Fig. 4, and temperature becomes higher on the upper side. Higher temperature is preferable for the high-temperature oxidation reactions to induce hot flame. In the case of 580 K, cool flame activated immediately the high-temperature oxidation reactions, and hot flame appeared in almost the same location where cool flame did. Neither cool flame nor hot flame appeared for \( T_a=560 \) K. Thus, the phenomena are dominated rather by buoyancy than by droplet interaction in normal gravity. Next, the experiments were performed in microgravity in order to focus on the droplet interaction.

### 3.2. Microgravity experiment

The result obtained by the drop experiment is shown in Fig. 7. Ambient temperature was 650 K. Unlike in normal gravity, \( d_0 \) was 0.8 mm considering the microgravity duration. In Fig. 7 (a), cool flame was not yet recognized, and the droplet pair was still in a quasi-steady vaporization state. Between Fig. 7 (a) and Fig. 7 (b), change in density field caused by cool flame was recognized. Though an exact location of cool-flame appearance is hard to be defined, it seems that change in fringes came from the right outer side of the droplet pair. As mentioned in Introduction, the previous studies showed that the mutual cooling effect was dominant before cool-flame appearance. In other words, temperature distribution is important for cool-flame appearance. Then

Fig. 7. Images of an igniting droplet pair through interferometry (fuel: \( n \)-decane, \( d_0=0.8 \) mm, \( P=0.3 \) MPa, \( T_a=650 \) K, \( l=2 \) mm, in \( \mu g \), 1000 fps).
one would expect that cool flame appears on the outer side of the droplet pair, since the temperature there is higher than that on the inner side. Since interferometer gives integrated information along the visual leg, the location of cool-flame appearance in the direction perpendicular to the plane containing four SiC fibers is still uncertain, and one should pay attention. However, the observed phenomena correspond with the expectation. At 330 ms, cool flame surrounded the right-side droplet. Subsequently, at 350 ms, cool flame also surrounded the left-side droplet. Ideally, cool flame is expected to appear on both right and left outer sides simultaneously if there is perfect symmetry. However, actually it is not the case. Probably because of the slight difference in d0 and initial asymmetry of temperature field, cool flame appeared first on the right side in this case.

At 527 ms, new fringes appeared suddenly in the location slightly lower than the middle point of two droplets. One ms after that, very steep density distribution, i.e., temperature distribution appeared between the droplets. This is caused by hot-flame appearance. The previous studies showed that the effect of duplicated fuel sources was dominant after cool-flame appearance. In other words, fuel-concentration distribution is important for hot-flame appearance. Obviously, fuel concentration between two droplets is higher than that on the outer side, and therefore one would expect that hot flame appears on the inner side of the droplet pair. The observed phenomena correspond with the discussion.

4. Conclusions

Droplet interaction is expected to affect the two-stage ignition of fuel droplet clouds through the development of temperature and fuel-concentration distribution. In order to study this effect, experiments on spontaneous ignition of an n-decane droplet pair in hot air were performed. Cool-flame and hot-flame behavior was observed by interferometry. In normal gravity, cool flame always appeared on the lower side of the droplet pair, and hot flame appeared on the upper side in most cases, which is obviously the effect of buoyancy. In microgravity, cool flame appeared on the outer side of the pair, and hot flame appeared on the inner side of the pair, which corresponds with the expectations obtained from the previous studies. However, different tendency might be observed in different experimental conditions. For example, if T_b is much higher, cool flame might appear on the inner side of the droplet pair, since too high temperature inhibits the low-temperature oxidation reactions. If T_b is much lower, hot flame might appear on the outer side as cool flame did, since lower T_b leads to shorter t_c as in normal gravity. Further experiments are expected.

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References