Effects of the Initial Heat-Up Period on a Two-Droplet Array Burning at High Pressure in Microgravity*

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The interactive combustion of two closely-spaced droplets at elevated pressures was investigated experimentally in a 2.2 second drop tower. Heptane, hexadecane and mixtures of the two were the fuel. A nitrogen-oxygen ambient with a relatively low oxygen concentration facilitated observation of droplets during combustion at elevated pressures. Results show that staged combustion of binary fuel droplets still exists for interacting droplets at elevated pressures. For pure fuels, the interaction effects are principally observed during the initial heating period. For fuel mixtures, interaction effects are estimated by comparing the transition time of a single droplet to that of the droplet pair.

Key Words: Combustion, Liquid Fuel, Diffusion Flame, Interaction Effects, High Pressure Combustion

1. Introduction

Understanding high pressure droplet combustion phenomena is of crucial importance in the study of spray combustion, since many practical combustors


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often operate at high pressure. High-pressure, isolated droplet combustion has been studied both experimentally and theoretically. Because of experimental difficulties, however, the results of these studies do not provide an entirely clear physical picture of high-pressure droplet combustion, and little information on high-pressure droplet combustion exists for multicomponent fuels, despite their practical importance. Dense sprays of practical interest at high pressures also exhibit the further complication of droplet interactions during combustion. Although there have been some experimental and theoretical studies on the influence of droplet interactions at atmospheric pressure, almost no information exists on the combustion of arrays of interacting droplets at high pressure.

For those reasons, we investigated the burning behavior of interacting droplet arrays by comparing the representative characteristics of staged combustion of binary-fuel droplets for both single droplets and droplet pairs(12)(13). We found that the burning rate constants of the first and the third stages, as well as the transition droplet volume, are not strongly affected by interaction(13). The burning lifetime, however, of the strongly interacting droplet pair exceeds that of the single droplet. The study also showed that
the droplet lifetime increased due to interaction and that the disparity in the lifetimes between the single droplets and droplet pairs decreases with pressure. In[4], we conducted binary-component droplet experiments and demonstrated that the mixture of two fuels increases the droplet lifetime. The increase in the burning lifetime for the fuel mixtures is probably related to the staged combustion behavior typical of binary fuel mixtures (the first stage involving vaporization of highly volatile component, the second stage a plateau associated with increasing surface temperature and the third stage involving vaporization of less volatile component as well[4,6]). In both studies, however, we could not investigate the droplet vaporization behavior during combustion at high pressure because of high light intensity emitted from flame (due to soot emission) at high pressures.

To enable observation of the burning droplets at high pressures, we conducted combustion experiments in the same pressure and fuel conditions as our previous studies[1,3] with a reduced oxygen mole fraction in the ambient gas[6]. In the previous report of this configuration, we investigated the effect of interactions by comparing the burning rate constant, and the droplet and flame lifetimes of single droplets and droplet pairs. The investigation demonstrated that the critical volume fraction at the onset of transition from the first to second stages and the burning rate constants of the first and the third stages are not affected strongly and that droplet lifetime is strongly dependent on the droplet spacing. The physical mechanism, however, that caused the increase of the droplet lifetime was not clarified.

Previous reports on interacting combustion of droplet arrays at atmospheric and sub-atmospheric pressures[7–9] showed that interaction effects are strongest in the initial heat-up period (the period before attainment quasi-steadiness of the liquid phase[10]). The present work seeks to determine whether this is true at higher pressures and for binary mixture droplets. In this paper, we will examine the effects of unsteadiness during the heat-up period at high pressure. This is the mechanism that is supposed to differentiate between the burning time of interacting droplets and that of a single droplet. The experiments, involving heptane-hexadecane mixtures in atmospheres of reduced oxygen content, are performed in microgravity. The microgravity environment minimizes the effects of buoyancy to better enable comparison with theory and prevents the droplets from falling off the suspending fibers as the surface tension diminishes with increasing pressure[11]. The suspending fibers keep the droplet in the field of view of the camera and also allow the inter–droplet separation distance to be fixed and known for the entire test.

2. Experimental Apparatus and Procedure

The combustion experiments were performed in microgravity in a droptower at the NASA John H. Glenn (formally Lewis) Research Center. The facility provides 2.2 seconds of microgravity, with an estimated gravity level less than $10^{-4}$ times normal gravity. Figure 1 shows the experimental apparatus which consists of a combustion chamber with glass windows, a fuel-supply system, a hot wire igniter, two black and white CCD cameras, a backlight, a computer control unit and a motor driver[11–13].

Two almost identical droplets were dispensed at the end of two identical 0.125 mm quartz fibers (with small beads on the end) in normal gravity just prior to the start of the drop. Two hot wires then ignited the droplets at the same time shortly after release of the experimental package into microgravity. The igniters were on for 0.2 seconds[10] (for all of the experiments) after which time they quickly retracted away from the droplets and the flame.

The ambient gas was a room-temperature nitrogen–oxygen mixture with an oxygen mole fraction of 0.12. The reduced oxygen concentration aided in visualizing the droplet at high pressure[6]. The initial droplet diameter, $d_0$, was approximately 0.9 mm ± 0.1 mm for all of the tests. The separation distance between the two droplets, l, was such that the ratio $l/d_0$ was approximately 1.7 ± 0.1 for all of the tests. This selection ensured a maximum departure from single-droplet behavior. The fuels were heptane, with a critical pressure of 2.74 MPa, hexadecane, with a critical pressure of 1.41 MPa, and mixtures of the two

![Fig. 1 A schematic of the experimental apparatus (1) High pressure combustion chamber, (2) Motor, (3) Camera #1 (backlit image), (4) Camera #2 (direct photograph), (5) Mirror, (6) 2 Batteries, (7) Transformer, (8) Manual driver, (9) Computer, (10) Video transmitter)](image-url)
with initial hexadecane mass fractions, $Y_0$, of 0.11, 0.33 and 0.63. The ambient pressure ranged from 1.0 MPa to 3.5 MPa.

Two orthogonal views of the combustion process were from two black and white CCD cameras through the windows of the combustion chamber. One view was backlit to visualize the droplet, and the other view shows a direct photograph of the flame. The images from the CCD cameras were transferred to a computer via a black and white frame grabber board for analysis. In the present experiments, the edges of the droplet and flame were quite easy to detect. For the droplet size measurements, the computer differentiated between the droplet and the background by a threshold intensity. The projected area of the droplet came from counting pixels inside the boundary of the droplet. The equivalent diameter reported in this paper is the diameter of the sphere that has the same projected area as that measured. The flame diameter of the droplet pair was the maximum diameter of the visible flame, namely that along an axis through the center of the two droplets.

3. Results and Discussion

3.1 General aspects and several definitions

Figure 2 shows a representative droplet history (d$^2$ squared as a function of time, t, each normalized by d$^2$) for a droplet pair with $Y_0=0.63$ burning in a 2.0 MPa ambient. This figure clearly reveals that the three-stage combustion of binary fuels (the first stage involving heptane vaporization, the second stage a plateau associated with increasing surface temperature and the third stage involving hexadecane vaporization as well), previously documented for single droplets, also occurs for interacting droplets. Figure 2 also defines several important quantities related to the burning behavior. $K_1$ and $K_3$ are the burning rate constants for the first and third stages, and are the maximum slopes of the droplet history in each stage. These maxima always occur at the end of the stage. The critical liquid droplet volume fraction ($V_c/V_0$) is the ratio of the droplet volume at the onset of the second stage, $d_2$, to the initial droplet volume, $d_0^3$ ($V_c/V_0 = d_2^3/d_0^3$). The droplet lifetime, $t_0$, is the time from the initial appearance of a luminous flame until the droplet disappears. The droplet lifetime is approximately proportional to $d_0^3$. All of the droplet lifetime data in this paper are corrected to droplet lifetimes based on $d_0=1$ mm. We also define the characteristic time of the second, $t_2$, and the third, $t_3$, stages, where by definition $(t_2/d_0^3 = t_3/d_0^3 + t_3/d_0^3)$.

Figure 3 shows a representative droplet diameter squared histories for a single droplet and a droplet pair (1/$d_0=1.78$) at a pressure of 2.0 MPa and initial hexadecane mass fraction, $Y_0$, of 0.63. This figure clearly shows that the burning time of the interacting droplet pair exceeds that of the single droplet. The single droplet flame history shows a nearly constant flame standoff until the flame contraction that marks the onset of the second stage. The flame standoff grows then until the end of the test. For the binary array, the flame contraction was at best barely perceptible. Instead, the two-droplet flame diameter remains nearly constant or decreases slowly with time after increasing for a short time early in the lifetime.

Figures 4 (a) and 4 (b) show the dependence of $K_1$ and $K_3$ on ambient pressure both for single droplets...
and droplet pairs, respectively. These figures show that, under most conditions and within experimental accuracy, droplet interactions have a fairly small influence on \( K_i \) and \( K_s \). The interaction effects are greatest for the pure fuels, whose spacing ratios, \( 1/d \), (\( d \) is the instantaneous droplet diameter) experience the greatest change during combustion (i.e., no staged burning behavior)\(^{14,15}\).

Figure 5 shows the dependence of the critical liquid droplet volume fraction (\( V_c/V_0 \)) on the initial hexadecane mass fraction (\( Y_0 \)) both for single droplets and droplet pairs. This figure also shows the theoretical analysis for single droplets by Shaw and coworkers\(^{14,15}\). The parameter \( \varepsilon \) is defined as \( \varepsilon = 8D_i/K_i \), where \( D_i \) is the binary liquid-phase diffusion coefficient and \( K_i \) is the burning rate constant in the first stage. Figure 5 shows all experimental data corresponds to values of \( \varepsilon \) between 0.05 and 0.20. This figure also shows that the normalized critical volume is not a strong function of either pressure or interactions, and is only a function of the initial hexadecane mass fraction.

Figure 6 shows the dependence of the droplet lifetime on pressure for pure heptane (\( Y_0 = 0 \)). Similar results were obtained for other values of \( Y_0 \). The droplet lifetime for both the single droplet and the droplet pair decreases with increasing pressure. The droplet lifetime for the droplet pair always exceeds that of single droplet. The difference between the droplet lifetimes of a single droplet and droplet pair decreases with increasing pressure. The lack of a
minimum in the droplet lifetime suggests that although the ambient pressure was above the critical pressure of both fuels for some of the tests, distinctive transcritical behavior was not present. This was probably because of nitrogen dilution effect\textsuperscript{(12a)(13)}. The video images also show no evidence of transcritical burning behavior.

3.2 Estimation of unsteady-interaction effects

Following Miyasaka and Law\textsuperscript{(19)}, we introduce the burning rate correction parameter:

$$\eta(d/d_0) = K(d/d_0) / K_0(d/d_0)$$  \hfill (1)

where $K(d/d_0)$ is the instantaneous burning rate constant of droplet pair and $K_0(d/d_0)$ is instantaneous burning rate constant of the single droplet, both of which are a function of the droplet diameter. We can only use this definition for the pure fuel tests, because the occurrence of staged combustion complicates the vaporization phenomena. Equation (1) clearly shows that $\eta=1$ represents no interaction. The greater the departure from unity, the greater the interaction effect. Theoretical quasi-steady analyses have shown that $\eta$ increases with instantaneous droplet separation ($l/d$) and eventually approaches unity\textsuperscript{(15)(16)}. The results of low pressure are qualitatively similar to the theoretical predictions. The gas-phase in these tests was probably quasi-steady, so agreement with theory is not surprising\textsuperscript{(8)}. The assumption of a quasi-steady gas-phase, however, becomes increasingly less valid as the pressure increases.

Figure 7 shows the dependence of $\eta$ on $l/d$ for three pressures. At $P=1.0$ MPa, the value of $\eta$ is relatively low early in the droplet lifetime (smaller $l/d$) and slowly approaches unity towards the end of the droplet lifetime. At $P=2.0$ MPa, $\eta$ approaches unity quickly and remains close to unity thereafter. At $P=3.0$ MPa, $\eta$ approaches unity quickly, similar to the test at $P=2.0$ MPa, reaches a maximum, then decreases in the middle of burn and slowly increases towards the end of the test.

Figures 8(a) and 8(b) show the time for the onset of the second stage ($t_c/d_0$, Fig. 8(a) and the time between the second and third stages ($t_{32}/d_0$, Fig. 8(b)) as a function of for three different pressures for both single droplet and droplet pairs. These characteristic times include both an unsteady-initial heat-up period and a quasi-steady vaporizing period for the first stage and the third stage. The transition time ($t_{c3}/d_0$) is another characteristic representing the onset of the second stage, like the critical volume fraction, $V_c/V_0$. Unlike Fig. 5, however, Fig. 8(a) shows effects due to both interactions and pressure. The transition time of the droplet pairs clearly exceeds

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig7.png}
\caption{Dependence of the burning rate correction parameter, $\eta(d/d_0)$, on the instantaneous separation distance, $l/d$, for three different pressures ($Y_0=0$)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig8.png}
\caption{Dependence of the transition time, $t_c/d_0$, and the second heat-up time, $t_{32}/d_0$, on initial hexadecane mass fraction, $Y_0$. (a) single droplet, (b) droplet pair}
\end{figure}

\textit{JSME International Journal}
that of a single droplet for each fuel composition and pressure. This difference between the single droplet and droplet pairs is smaller at larger values of $Y_0$. We believe that this is due to a longer heat-up period for the interacting droplets. The envelope flame that surrounds the droplet pair creates an asymmetric gas phase temperature distribution. This temperature gradient is smaller between the droplets and this results in a longer transient heating period, and consequently longer $t_c$.

Figure 8(b) shows that the value of $t_{d2}/d\delta$ remains nearly constant for the single droplet and increases for the droplet pair with increases in the initial hexadecane mass fraction. When $Y_0=0.11$, $t_{d2}/d\delta$ of the droplet pairs is smaller than that of the single droplets for each pressure. From Fig. 8(a), the first heat-up period, $t_c/d\delta$, for $Y_0=0.11$ is large and thus the liquid droplet should be heated for a longer time. This would tend to make $t_{d2}/d\delta$ shorter. For $Y_0=0.63$, $t_{d2}/d\delta$ of the droplet pairs exceeds that of the single droplet. This is because the transition occurs early in the droplet lifetime (small $t_c/d\delta$) and the heat up of the liquid is not complete (compared to large $t_c/d\delta$). For $Y_0=0.33$, such a distinction could not be made.

The results from Figs. 8(a) and 8(b) demonstrate that the interaction effects on the vaporization characteristics of the first stage and the third stage are well explained by changes in the initial heat-up behavior.

4. Conclusion

In this paper, we investigated interaction effects on a binary droplet array at high pressure by examining the droplet vaporization behavior in the initial heat-up period. The main conclusions of this paper are as follows:

1. The interaction effects between two droplets during combustion still exist even at high pressure conditions. The increase of the droplet lifetime due to interaction depends on the extent of the liquid-phase unsteadiness.

2. The asymmetry caused by the envelope flame in a burning droplet pair results in a reduction of the temperature gradient near the fuel surface. This lengthens the time to the onset of the second stage compared to that of a single droplet in the same ambient.

3. Both the initial heat-up period and the second heat-up time are affected by interactions.

Acknowledgments

This work was performed under the management of the Japan Space Utilization Promotion Center (JSUP) as a part of the R & D project of the Advanced Combustion Science Utilizing Microgravity supported by the New Energy and Industrial Technology Development Organization (NEDO). FAW acknowledges the support of the NASA Glenn Research Center through grant No. NAG-1889 in the microgravity science program. The helpful advice of M. Mikami of Yamaguchi University is gratefully acknowledged.

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