HIGH-PRESSURE COMBUSTION OF BINARY FUEL SPRAYS

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INTRODUCTION

The research addressed here represents a small cooperative project between the US and Japan. The authors have now been involved in this project for a number of years. In previous workshops, the presentation has focused narrowly on the specific most recent accomplishment. If this tradition were followed again, then material about to be published [1] would form the basis of the present write-up. At the present stage, however, it may be of greater interest to step back and take a longer look at the overall character of the project and its history. The recent accomplishments therefore will be covered here only in an abbreviated manner.

SCIENTIFIC OBJECTIVE

The general scientific objective of this research, reflected in the title of this presentation, the current title of the US portion of the project, is to advance knowledge that can contribute to improvements in practical applications of spray combustion. Recognizing that practical interest centers mostly on high pressures and multicomponent fuels, the investigators chose to explore conditions up to critical pressures and to include binary liquid fuel mixtures as model systems with relevance to multicomponent fuels. Studies centered on single droplets, to the extent that their individual combustion characteristics were unknown, and on linear arrays of droplets, to obtain information on droplet-interaction effects having bearing on spray combustion. Intending to be fundamental, the investigation avoided the complexity of working with sprays themselves. It was never intended to go beyond arrays, and in fact most of the studies concerned droplet pairs and single droplets. In recent years, interest has progressed to the consideration of additional effects that might be employed to augment performance of spray combustion, namely effects of acoustic fields [1] and of electric fields. Embracing a wide range of physical phenomena, the work has explored a number of avenues for improving ideas about spray combustion.

ORGANIZATION

The project was organized in an attempt to establish, for the first time, a small-scale cooperative research program between Japan and the US in microgravity combustion. J. Sato of IHI was a prime mover in this organization. The universities involved are the University of Tokyo, where this research is led by M. Kono, and UCSD, where the research is led by F.A. Williams. The research includes experiments performed in the 2.2 second drop tower at NASA Glenn Research Center, with D.L. Dietrich overseeing the experiments. Graduate students from the University of Tokyo are involved in these drop-tower experiments and also perform experiments in a smaller drop tower at their own university. The graduate students who have (sequentially) participated in the project in this way are M. Mikami (now a professor at another university in Japan), O. Habara, K. Okai and, most recently, T. Ueda. The student typically visits Cleveland for about two months twice a year to perform experiments and then spends a week or two in San Diego analyzing the results with F.A. Williams before returning to Tokyo. The meanings of the experimental results, their theoretical interpretations and the associated new theoretical developments that are needed are then addressed by all of the investigators at their respective locations, with communications by mail, phone, fax and especially e-mail. These relatively recent advances in communications have been essential in making this cooperative program possible. The program is notably economical, with all of the work and travel of the Japanese investigators supported by Japan and of the US investigators by NASA.

HISTORY

The specific problems addressed in the research are determined jointly through discussions among the Japanese and US investigators. Following these discussions, first the combustion of single droplets of mixtures of heptane and hexadane was investigated in reduced-oxygen atmospheres at pressures up to 3 MPa [2]. The droplets studied are fiber-supported and nominally of about 1 mm initial droplet diameter. Extending pressures to 6 MPa in air demonstrated the importance of accounting for three-component phase diagrams involving dissolution of inert gas in the liquid near the critical point if observed variations of minima of burning times are to be properly explained [3]

Having developed an understanding of single-droplet behavior, it was decided to investigate effects of interactions of droplets of these same fuels burning under these same atmospheric conditions. Closely spaced droplets were shown to exhibit increased burning lifetimes, there being a minimum in the lifetime at a critical interdroplet spacing [4]. For fuels that are mixtures of methanol and dodecanol, however, burning at pressures up to 9 MPa, the minimum is not present at any interdroplet spacing because the radiative augmentation of burning rates is insufficiently strong [5]. The most recent experiments in the 2.2 second tower employed single droplets with mirrors and other obstacles nearby to further clarify effects of radiation interactions [6]; these experiments showed significant influences of the obstacles on the flow fields under microgravity, with flow effects distorting flame shapes and generally outweighing radiation effects.

The work is thus seen to have progressed from studies of single droplets of pure fuels at pressures up to values in the vicinity of the critical pressure, to studies of single droplets of binary fuel mixtures at pressures up to critical (with staged and disruptive burning behaviors identified), to studies of interactions of arrays of pure-fuel and binary-mixture droplets, for different fuel pairs (alkanes and alcohols), again up to the vicinity of critical pressures. The information obtained in this way was judged to provide some understanding of droplet combustion behaviors relevant to high-pressure spray combustion, sufficient to proceed to investigate additional complicating effects that may be of benefit in spray-combustion applications. With this in mind, new apparatus was built for the purpose of measuring influences of acoustic and electric fields on the combustion of single droplets and of droplet pairs. Measurements have now been made of each of these effects separately, for both single droplets and droplet pairs, but as yet only for octane droplets burning in air at normal atmospheric pressure under normal and microgravity. The results are discussed in the following sections.

EFFECTS OF ELECTRIC FIELDS

To date, the experiments in the electric fields have been performed only in the small drop tower at the University of Tokyo. Initial droplet diameters were about 0.75 mm, and field strengths ranged up to 50,000 V/m. The effect of the field on the flame appears to be much stronger in microgravity than in normal gravity. The flame around a single droplet is attracted towards the negatively charged electrode, as anticipated from the belief that the ions and soot particles are predominantly positively charged. The burning rate of the droplet is slightly higher at the highest field strengths, as might be expected from the effect of the electric wind. At sufficiently high field strengths, there seems to be periodic emissions of burning soot particles through the flame, mainly towards the negatively charged electrode. These behaviors of single droplets may qualitatively be expected in advance.

For droplet pairs, the observed behaviors are more complex and in some ways counterintuitive. The experiments were performed with the electric field parallel to the axis between the centers of the droplets. For interdroplet separation distances small enough that the flame surrounds both droplets in the absence of the field, the electric field reduces the extent of droplet engulfment by the flame, tending to form separate flames around each droplet, and those two flames are aymmetrical, with the brighter flame located on the side towards the positive electrode, as if the flame on the side towards the negative electrode were subjected to a convective velocity from the electric wind that lengthens and narrows it, reducing is total luminosity. At larger interdroplet separation distances, the visible yellow flame around each droplet separately tends to be elongated towards the nearest electrode, which is unexpected for the flame near the positive electrode since it suggests that the electric wind is dominated by negatively charged particles there. The possible occurrence of negatively charged soot particles is supported by the observation that, although most burning soot particles are emitted in the direction of the negative electrode, some are emitted in the direction of the positive electrode, even for single burning droplets if the electric field is sufficiently high. Visible flames thus are narrowed by the field and protrude not only in the direction of the negative electrode but also to some extent in the direction of the positive electrode, perhaps under the combined effects of positively and negatively charged particles in the flame.

EFFECTS OF ACOUSTIC FIELDS

Measurements of the influences of acoustic fields on the microgravity combustion of single droplets and of droplet pairs employed a loud speaker at the bottom of the chamber to produce the acoustic field [1]. Experimental results for single droplets showed that, at low frequency and small to moderate acoustic intensities, the evaporation rate increases with increasing acoustic field strength, with the burning-rate constant k nearly proportional to the product of frequency, f, and square of displacement, X^2, that is,

$$k = k_0\left(1 + \alpha f X^2\right), \tag{1}$$

where k_0 denotes the burning-rate constant in the absence of the field, and α is a constant. At higher acoustic intensities, the burning-rate constant either remains constant or decreases, and, in some cases, flame extinction occurs at a finite flame diameter. The experimental results extending to these higher intensities can be fit by the formula

$$k = k_0 + AfX^2\left[1 - fX^2/(2D)\right], \tag{2}$$

with the value of the nondimensional constant A being about 0.03 and the critical acoustic diffusivity D at which the burning-rate constant is a maximum having a value of about 10 mm^2/s. Theoretical explanations for these experimentally observed values of the parameters are still under investigation.

Results of a representative experiment are shown in Fig. 1, where the acoustic velocity is defined a $V_a = 2\pi fX$, d denotes the droplet diameter, its initial value being d_o, t is time, and the visible flame height H in the direction of the acoustic field and width W perpendicular to that direction are obtained from a CCD cameral. Experimental details are given elsewhere [1]. It is seen that H/d_o and W/d_o both plateau, with W/d_o larger than H/d_o as a consequence of the gas motions induced by the acoustic field.

Figure 2, where l denotes the interdroplet spacing, shows corresponding results for droplet pairs, at acoustic intensities giving X of order 0.1 mm. The acoustic field is applied here perpendicular to the axis between the two droplets and is seen to increase the burning-rate constant under the conditions of the experiment, and the flame height decreases with increasing frequency. The burning-rate constant for a droplet pair is consistently lower than that of the single droplets. At lower frequencies, the burning-rate constant reaches a maximum at an intermediate acoustic intensity for droplet pairs, and at higher frequencies it increases monotonically with increasing acoustic intensity. The flame size decreases as a result of interactions, as does the critical spacing for the formation of a merge flame around the droplet pair, rather than having individual flames surrounding the droplets. The results also show that interactions stabilize the flame, in that droplet pairs burn to completion under conditions where the flame surrounding a single droplet extinguishes at a finite droplet diameter. Figure 3 shows the variety of different shapes of flames around droplet pairs that can be produced by the acoustic field [1]; the droplet separations are all horizontal, and the arrows at the edges identify the direction of application of the acoustic field, which is parallel to the interdroplet axis in the third frame (c). Explanations of these results currently are undergoing further study.

FUTURE WORK

This program is planned to continue to study influences of electric and acoustic fields on the combustion of single droplets and droplet pairs. In addition to attempting to clarify better the physical reasons for the effects described above, it is intended to consider fuels other than octane and influences of pressures above atmospheric, to better ascertain how acoustic and electric fields may affect spray combustion under conditions of greater practical interest. Many challenging questions clearly remain to be addressed.

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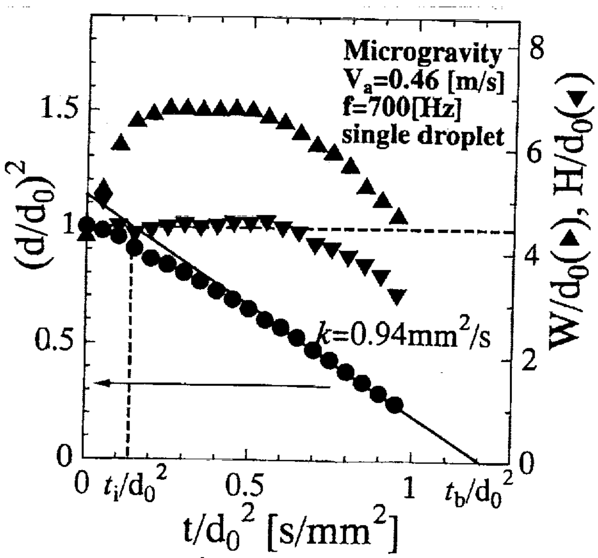


Figure 1: Histories of droplet diameters and flame characteristics for combustion of a single droplet in an acoustic field.

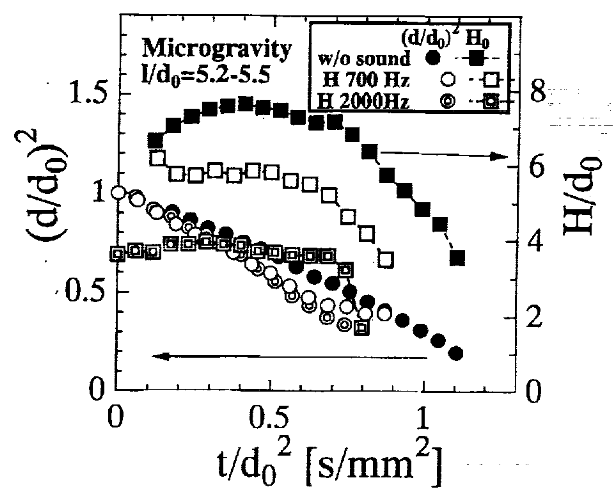
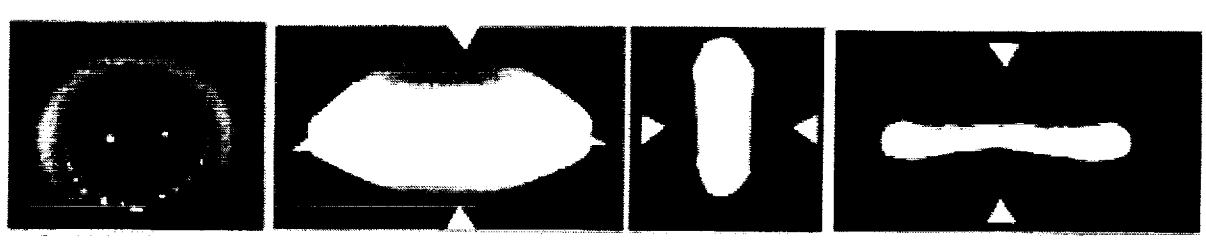


Figure 2: Histories of droplet diameters and flame characteristics for combustion of droplet pairs in acoustic field.



(a) no sound (l/d$_0$=2.3) (b) V_a = 0.27m/s (f=700Hz, *H*, l/d$_0$=2.7) (c) V_a = 0.57m/s (f=700Hz, *P*, l/d$_0$=2.7) (d) V_a = 1.31m/s (f=2000Hz, *H*, l/d$_0$=5.2)

Figure 3: Typical direct photographs of flames for burning droplet pairs in acoustic fields.