COMBUSTION EXPERIMENTS IN REDUCED GRAVITY WITH

TWO-COMPONENT MISCIBLE DROPLETS

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Introduction

The combustion of liquid fuels is a topic worthy of scientific attention on practical and fundamental grounds. Most practical applications of liquid-fuel combustion involve the formation of spray diffusion flames, where droplets frequently burn in groups rather than individually. The combustion is typically complex, with interactions occurring between various physical mechanisms.

Many efforts to understand liquid sprays have focused upon studying isolated droplets. Information gained from these studies is often not directly transferable to spray situations. However, isolated-droplet studies are useful in that they allow certain phenomena (e.g., extinction) to be studied under well-controlled and simplified conditions. When theory and experiment agree for simplified situations, predictions for more complex cases (where accurate experimental data may not exist) may be made with more confidence. The simplest droplet combustion scenario is that of an isolated droplet undergoing spherically-symmetric combustion in an environment of infinite extent. This idealization is approached only when forced and buoyant convection are negligible, the droplet is unsupported, and all foreign objects are far-removed from the combustion zone. Appreciable gravity levels compromise spherical symmetry by inducing buoyant convection.

In practice, liquid fuels are usually multicomponent. It is important to understand the vaporization mechanisms of multicomponent fuels, especially the rates that fuel components with differing properties are vaporized from the liquid phase. This is because gas-phase phenomena depend on the components that have been vaporized, while liquid-phase phenomena depend on the components remaining in the liquid. The simplest multicomponent fuels are (arguably) binary and miscible. Studying binary miscible fuels is useful because they exhibit phenomena which do not appear with pure fuels but which are characteristic of multicomponent blends, for example influences of volatility differences and liquid-phase species diffusion.[3]

Though small droplets are of practical concern (e.g., < 50 μm as found in some spray systems), it is difficult to performed detailed experiments with them. This is because small droplets are difficult to deploy and ignite without significant perturbations, and they may be difficult to resolve photographically. Hence, most detailed investigations into single-droplet combustion have focused upon larger droplets which are easily observed. In this program, reduced-gravity combustion behaviors of miscible binary droplets initially about 1 mm in diameter are studied. Gravity levels significantly less than 10^{-3} g's are required to make buoyancy effects negligible for these size droplets.

Vaporization histories of binary miscible droplets may be significantly different than for pure fuels. When there is a significant volatility difference between droplet components and the lower-volatility component is initially present in small amounts, binary droplets may exhibit a two-staged combustion history where two periods of nearly d-square-law combustion (i.e., where the square of the droplet diameter decreases linearly with time) are separated by an intermediate period where vaporization rates are low and flame diameters decrease significantly. These behaviors are thought to be a result of a sudden buildup of the lower-volatility component at the droplet surface [1,2], necessitating a sudden increase in the droplet surface temperature. While the droplet is heating, the flame contracts because more of the energy transported to

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[3]Exceptions do exist for initially-pure fuels. For example methanol droplets may absorb water from the gas phase.

the liquid is used for heating rather than simply for vaporization. Asymptotic analyses of these phenomena are reported in [2]. During the first period of d-square-law vaporization, most of the fuel being vaporized is the higher-volatility component, while during the second d-square-law vaporization period, if liquid-phase species diffusivities are sufficiently small, both liquid components are vaporized at rates that are nearly proportional to their average liquid mass fractions [3]. This mode of combustion, where both liquid components are vaporized at rates that are nearly proportional to their average liquid mass fractions, may be termed the diffusion limit. Recent experiments [4] have suggested that liquid-phase species diffusion may be more rapid than previously thought such that liquid-phase behaviors are intermediate between the diffusion limit and the batch distillation mode. The experiments in Ref. [4] were performed in normal earth gravity and with convective environments, so it is possible that convection may have played a role in promoting liquid-phase transport.

For binary mixture droplets undergoing combustion, the surface concentration of the lower volatility component will generally tend to increase with time. Because liquid species diffusion is typically slow relative to droplet surface regression rates, chemical stratification may occur in the droplet such that the droplet interior has a higher mass fraction of high-volatility component than the droplet surface. During combustion, the temperature at the droplet surface will tend to approach the boiling temperature of the liquid surface mixture. Since Lewis numbers for liquids are typically large relative to unity, the droplet interior may be heated above temperatures required for bubble nucleation and growth. As a result, a bubble may grow and eventually fragment a droplet (the droplet may experience a "disruption" or "microexplosion"). These phenomena have been observed in normal-gravity experiments for multicomponent mixtures [1,5-7]. Disruption has also been observed in reduced-gravity experiments on combustion of unsupported droplets initially composed only of n-decane [8]; similar disruptions of n-decane under normal-gravity conditions appear not to have been reported in the literature. The mechanism behind disruption of n-decane droplets in reduced gravity has not yet been clearly identified, though it has been postulated that disruption may be related to sooting behavior [2,8].

Experiments in reduced gravity should yield insights into the efficiency of liquid-phase species diffusion, since this diffusion may markedly influence combustion behaviors, as described above for the two-staged combustion behaviors. By noting times for flame contraction to occur with mixtures that exhibit two-staged combustion behaviors, calculations for effective liquid-phase species diffusivities may be made (e.g., with the asymptotic theory in [2], or with numerical models). Finally, sooting behavior may be significantly different during the two d^2-law periods since gas-phase compositions may differ significantly. Differences in sooting may be observable photographically by noting behaviors of apparent flame luminosities and soot particles large enough to be observed.

Scientific Objectives

This research focuses on the combustion of binary miscible droplets. Experiments are performed at the NASA Lewis 2.2 sec drop tower in Cleveland, Ohio. Mixtures of n-heptane and n-hexadecane are presently being studied, providing significant variations in component volatilities. The objectives are to gather data on the following:

(1)   Transient droplet diameters (including two-staged combustion behaviors and disruption).
(2)   Transient flame behaviors (including sudden flame contraction as discussed above, and extinction).
(3)   Transport of observable soot particles.

Obtaining these data will be useful in several respects. Knowledge of transient droplet and flame diameters will provide an experimental base from which comparisons between theory and experiment may be made. Working with droplets composed of high-volatility and a low-volatility components, with the latter initially present in small amounts relative to the former, should allow the sudden-flame-contraction behaviors discussed previously to be observed. By noting times for sudden-flame contraction to occur, estimates of liquid-phase species diffusivities may be made. These data will also be useful for development and validation of detailed numerical models.

Work Performed To Date

Digital Image Processing System - A Sun workstation-based digital image processing system has been developed and constructed for analysis of cine films from drop tower experiments. Basic concepts for this system were obtained from Ref. [9], where a PC-based digital image processing system is described. Software for the Sun-based system has been developed with the assistance of Virtual Visions Software[4].

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Drop Tower Experiments - During the summer of 1992, experiments with n-heptane/n-hexadecane mixture droplets were performed at the NASA Lewis Research Center 2.2 sec drop tower. An existing droplet combustion apparatus available at NASA Lewis was used for these experiments; this apparatus is described elsewhere [10]. Experiments were attempted both with and without a ceramic support fiber ($\approx$ 10 μm diameter) being present. The ceramic fiber was utilized to prevent significant droplet drift after deployment. The fiber assembly used in the present experiments was developed by D. Dietrich[5]. Twenty-two experiments were performed, both with and without the fiber. Initial droplet compositions, environmental compositions, and pressures were varied in the experiments. Four experiments were successful, with droplets that had low deployment velocities (a few mm/s or less). The other experiments were unsuccessful for various reasons, the most common of which was large residual deployment velocities that caused droplets to quickly leave the camera field of view, even when the fiber was used.

The four successful experiments all utilized the support fiber - data was not obtained for unsupported droplets. Droplets in the successful experiments were burned in air at 1 atm, and involved using initial droplet hexadecane mass fractions of 0, 20, 40 and 60%. In the experiments, two cine cameras with orthogonal fields of view were used to simultaneously record liquid droplet and flame behaviors. Photography of liquid droplets involved backlighting, while flames were photographed without backlighting.

Preliminary analyses of the cine films have been performed with the workstation-based image processing system. Further processing is needed to complete analysis of these films. The image processing system was used to measure droplet diameter histories from the four films, as well as the flame diameter history for one film. Shown in Fig 1. are plots of the squares of the droplet diameters (d^2) vs. time for the four successful experiments. Data are plotted for the time period from spark ignition until the droplets either became too small to image or the drop package hit the bottom of the drop tower. The percentages listed are the initial hexadecane liquid mass fractions. After decay of initial transients, droplet diameter histories appear to show regions where the d-square-law approximately holds. Only the experiment with a 20% hexadecane initial mass fraction appears to clearly show a plateau in the d^2 vs. time plot, indicative of droplet heating. Cine films of the flame behavior for this experiment show the flame to grow, contract, and then grow again over a time period near when the plateau in the d^2 plot in Fig. 1 appears. A sequence of three pictures showing the flame behavior over this time period is shown in Fig. 2. Times in this figure are after ignition, and show the flame prior to contraction, after the flame has contracted (the flame was very dim during this time), and later when it begins to grow in size again. Squares of measured droplet and flame diameters for this experiment are shown in Fig. 3, where it is seen that the onset of flame contraction occurs just prior to the onset of the plateau in the droplet diameter history. Flame diameters in Fig. 3 were measured perpendicular to the fiber.

In the films, it was evident that the fiber was influencing combustion to some extent. For example, soot particles large enough to be seen were sometimes observed to migrate to the fiber and accumulate there. The flames in Fig. 2 are elongated along the fiber, suggesting an influence of the fiber. Shown in Fig. 4. is an image of a droplet, initially 60% hexadecane, 0.39 sec after ignition. The observable soot "shell" is not spherical, though it does appear to be somewhat symmetric about the support fiber axis. In the cine film, soot can be seen to accumulate at the fiber as time progresses. Glowing of support fibers in the hotter portions of the flames was also observed. This is evident in Fig. 2, where the bright, horizontal streaks in each image are actually the glowing fiber. How the radiative heat loss associated with this glowing affects combustion has not yet been evaluated.

Cine films of combustion of a droplet composed initially of 100% n-heptane showed evidence of what appears to be a microexplosion. A sequence of images showing the flame behavior just prior to, during, and after the microexplosion are shown in Fig. 5. This event appears to have caused the droplet to have lost an appreciable amount of mass in a short time period, as is evident in the d^2 plot of Fig. 1 by the "kink" in the data that appears between about 0.3 and 0.4 sec.

Future Plans

Design and Construction of Droplet Combustion Apparatus - A droplet combustion apparatus for use in the NASA Lewis 2.2 sec drop tower is being developed and constructed at UC Davis. This apparatus is projected to be ready for use in late fall 1992. To improve experiment success rates, improvements will be incorporated. For example, it is difficult with the apparatus presently available at NASA Lewis to accurately set the deployment needles and ignition electrodes to desired tolerances, resulting in many failed experiments because of bad droplet deployment or ignition. The new apparatus will incorporate positioning equipment that should allow accurate and repeatable placement of ignition electrodes and deployment needles prior to each experiment. Efforts will also be directed at providing suitably-matched pairs of droplet deployment needles.

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The new apparatus being constructed is projected to use scanner motor technology previously applied in older versions of the apparatus (for droplet deployment, scanner motors were used to simultaneously retract two opposed deployment needles between which droplets were grown [10]). Preliminary tests by NASA Lewis personnel have suggested that the use of DC motors with retraction speeds significantly higher than scanner motors may result in very small residual droplet deployment velocities and significantly higher experiment success rates. This DC motor technology, still under development, will be considered for use in the apparatus being built at UC Davis.

Drop Tower Experiments - The UC Davis drop apparatus will be used for more experiments with n-heptane/n-hexadecane mixtures. Experiments will be done with different initial environmental compositions and pressures. Initial oxygen mole fractions from about 0.1 to 0.5 and initial pressures from 0.5 to 2 atm will be used. Different inerts will be used in the gas phase to enhance or inhibit certain phenomena. For example, He may be used to increase average gas phase transport properties, promoting extinction and higher burning rates [11], while CO_2 may possibly be used to inhibit soot formation [12].

It may be important to inhibit soot formation in these experiments. Flame contractions and droplet disruptions have previously been observed for n-decane droplets burning in low-gravity environments [8], as well as the n-heptane droplet described above. These behaviors, which were unexpected for single component fuels, have been postulated to result from sooting effects [2,8]. If this is correct, flame contractions and droplet disruptions arising from surface buildup of the less volatile component in a binary fuel droplet may be influenced to an unknown extent by sooting, making interpretation of experimental results difficult. Experiments will be performed to search for conditions where sooting appears to influence combustion negligibly. Alcohol mixtures (which should tend to soot less than hydrocarbons) may also be used, though alcohols may absorb water into the liquid phase.

Image Processing System - Films are currently processed manually with the image processing system. The image processing system will be automated to allow a large number of frames to be rapidly processed from each film strip. In addition, data is presently taken from films by manually setting a threshold corresponding to the perceived droplet diameter. Edge detection algorithms will be incorporated into the image processing program, allowing more repeatable and accurate measurement of droplet diameters.

Computational Modeling - Efforts to provide numerical data for comparison with experimental results have been initiated. Professor H. A. Dwyer of UC Davis is the principal architect of the models presently being utilized. Briefly, the models assume that spherical symmetry exists in the gas and liquid phases. The governing equations are cast in a finite-volume form, and solved numerically for transient liquid- and gas-phase variables. Variable properties in both the liquid and gas phases are allowed. Complex chemical kinetics in the gas phase can be modeled, as well as global one-step reaction schemes. Initial results from this model were not available at the time this paper was written, but are expected to be available in the near future. Calculations are performed using the Sun workstation also used for image processing.

Other - To aid interpretation of experimental efforts, studies of allowable acceleration levels and durations will be performed. Issues such as droplet oscillation amplitudes, oscillation decay times, pre-ignition vaporization, etc., will be considered. In addition to being relevant to drop tower experiments, such studies will be germane to possible future flight experiments involving droplet combustion.

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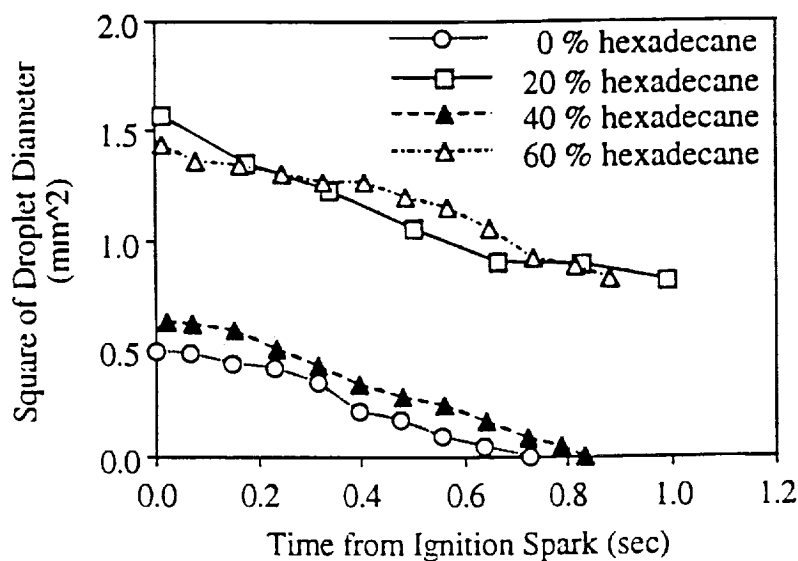
Figure 1.--Plots of squares of measured droplet diameters vs. time.

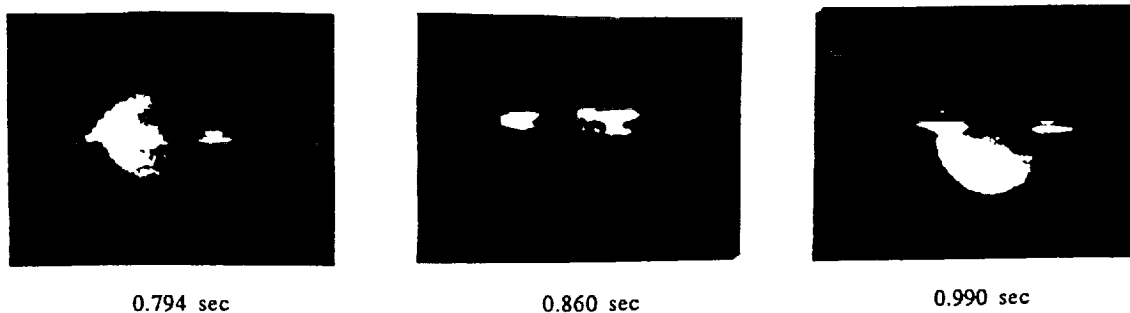0.794 sec   0.860 sec   0.990 sec

Figure 2.--Sequence of images showing flame contraction and growth for a droplet composed initially of 20% n-hexadecane and 80% n-heptane. Times are after the ignition spark. Visible flame diameters (measured perpendicular to the fiber) for this droplet are plotted in Fig. 3.
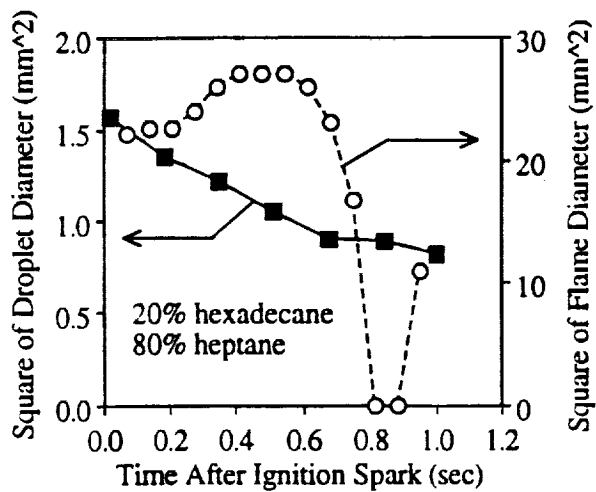
See Color Plate G2A

Figure 3.--Plots of squares of droplet and flame diameters for a droplet composed initially of 20% n-hexadecane and 80% n-heptane.

Figure 4.--Image of a droplet (initially 60% n-hexadecane and 40% n-heptane) showing the support fiber and the soot "shell". The droplet diameter is about 1.07 mm.

| 0.324 sec | 0.333 sec | 0.342 sec |

Figure 5.--Sequence of images showing the flame behavior just prior to, during and after what appears to be disruption of a droplet initially composed only of n-heptane. Times are after the ignition spark. For a scale reference, the visible flame diameter at 0.324 sec is about 4.7 mm (measured perpendicular to the fiber).

See Color Plate G2b

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